1995-09

"BUGS" Basic Unexploded Ordnance Gathering System: effectiveness of small cheap robotics

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NPS-ME-95-002

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

"BUGS" BASIC UNEXPLODED ORDNANCE GATHERING SYSTEM: EFFECTIVENESS OF SMALL CHEAP ROBOTICS

by
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June 1995

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Prepared for:
NAVEODTECHDIV R&D Center
Indian Head, Md 20640

Rear Admiral Thomas A. Mercer

Superintendent

Naval Postgraduate School

This thesis was prepared in conjunction with research sponsored in part by the NAVEODTECHDIV under funding number N0464A95WR01915.

Released by:

P.J. Marto

P.J. MARTO, Dean of Research

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*
2. REPORT DATE June 1995
3. REPORT TYPE AND DATES COVERED Master's Thesis
4. TITLE AND SUBTITLE "BUGS" BASIC UNEXPLODED ORDNANCE GATHERING SYSTEM: EFFECTIVENESS OF SMALL CHEAP ROBOTICS
5. FUNDING NUMBERS N0464A95WR01915
6. AUTHOR Jenkins, David A.
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000
8. PERFORMING ORGANIZATION REPORT NUMBER NPS-ME-95-002
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) NAVEODTECDIV R&D Dept, Indian Head, Md 20640
10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE *

13. ABSTRACT *(maximum 200 words)*

The subject of ordnance range remediation has received new emphasis in light of recent world events, particularly in the Middle East. The challenge of safely clearing ordnance fields of Unexploded Ordnance (UXO) is a serious one, that points to the use of new small robotic machines that can perform the cleanup task without human hands. Strategies that combine the best use of a variety of both highly capable and less capable, but inexpensive robots hold great promise. The Navy's Explosive Ordnance Disposal Technical Center has developed a "BUGS" Basic UXO Gathering System, in order to examine such strategies. In support of this effort, simulations are being conducted in order to examine the effects of navigation and control system characteristics on clearance for an inexpensive robotic vehicle in a typical BUGS clearance scenario, and to verify the clearance penalty inherent in a "pick up and carry away" operation.

14. SUBJECT TERMS BUGS, Unexploded Ordnance, Gathering, Small Cheap Robotics
15. NUMBER OF PAGES 96
16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified
18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified
19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified
20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

Approved for public release; distribution is unlimited.

"BUGS" BASIC UNEXPLODED ORDNANCE GATHERING SYSTEM: EFFECTIVENESS OF SMALL CHEAP ROBOTICS

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING
from the
NAVAL POSTGRADUATE SCHOOL
June 1995

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ABSTRACT

The subject of ordnance range remediation has received new emphasis in light of recent world events, particularly in the Middle East. The challenge of safely clearing ordnance fields of Unexploded Ordnance (UXO) is a serious one, that points to the use of new small robotic machines that can perform the cleanup task without human hands. Strategies that combine the best use of a variety of both highly capable and less capable, but inexpensive robots hold great promise. The Navy's Explosive Ordnance Disposal Technical Center has developed a "BUGS" Basic UXO Gathering System, in order to examine such strategies. In support of this effort, simulations are being conducted in order to examine the effects of navigation and control system characteristics on clearance for an inexpensive robotic vehicle in a typical BUGS clearance scenario, and to verify the clearance penalty inherent in a "pick up and carry away" operation.

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ACKNOWLEDGEMENT

I would like to acknowledge the financial support of the NAVEODTECHDIV for providing the research funding for this thesis. In addition, I would like to thank Foster Miller Inc., IS Robotics, Rockwell Science Center, K2T Inc., and Draper Laboratory for graciously providing information and pictures of their products, that appear in Chapter II.

I would also like to thank LCDR John Hosford, of the Operations Research Department at NPS, for tolerating my many sometimes very basic questions on the subject of probability and search theory, and for being a good friend and neighbor.

I would like to particularly express my gratitude for being fortunate to have worked with Professor Healey on this thesis. Professor Healey's broad controls systems experience and understanding are immediately apparent. He was always available, and was always able to patiently make control systems issues understandable. Professor Healey is an obvious asset to NPS. Thanks also to Professor Don Brutzman, who lent a second critical eye to this thesis.

I would also like to thank my mother, Professor Helen Jenkins, who I am most proud of. She is largely responsible for my search for higher education, and offered me the sound advice that, for a thesis, I should pick the professor, and not the subject. Her advice has been, and continues to be an inspiration, and is most certainly accurate, especially with Professor Healey.

Lastly, and most importantly, I would like to thank my wife Martha, and my two boys Eric and Jon, who always seemed to understand when I had to study. I will always appreciate the understanding and quiet time that helped me to achieve this educational goal.

I. INTRODUCTION

A. THE PROBLEM

The problem of range clearance following delivery of some current weapons systems is a serious one. Literally thousands of submunitions or other lethal battlefield weapons can be distributed over a football field sized area in seconds, with a few artillery tube or rocket salvos. For example, the Army's Multiple Launch Rocket System can deliver thousands of submunitions onto an area the size of several football fields. Assuming a nominal 5% dud rate, this could leave several hundred unexploded ordnance items in a field of only approximately a hundred by a hundred meters.

Current range clearance tactics involve the use of manned squads to identify, and either carry away or blow in place any unexploded ordnance (UXO). Unfortunately, when the human element is a part of any potentially live ordnance clearance situation, casualties eventually result. For example, in the recent Gulf War experience, both the Army and Marine Corps lost several personnel due to submunition clearance operations. The tragic loss of human life in such situations points to the need for autonomous range clearance systems that can perform the cleanup job without human hands.

B. THE CHALLENGE, AND ISSUES EXAMINED

The challenge then, is to effectively and quickly clear a range littered with unexploded ordnance without the use of manned squads. Many issues surround this challenge, and it has been suggested recently within the Navy's EOD Community that the use of small robotics will play an important role, although that role has yet to be defined.

The problem is that UXO clearance requires sophisticated sensor systems to detect the UXO in the presence of battlefield clutter and other items such as rocks, or vegetation. Once the UXO has been detected, it must be approached, defused or neutralized, and then

removed from the site. These later operations are high risk operations, where expensive, sophisticated robots could be lost. On the other hand, small cheap robots could be better used in the high risk elements of the operation if they had sufficient capability and a low enough cost to make the price of UXO clearance cost effective.

One proposal is to combine assets of differing capabilities and cost to provide the most effective overall technique for clearance. It then becomes important to study the impact of performance of small cheap robotic vehicles, and how increases in capability and cost make clearance operations more effective. The NAVEODTECHDIV has been working with a radio controlled teleoperated vehicle called RECORM (Figure 2.1) that will have the capability to provide video images of the terrain/clutter to a remote operator who could then detect, classify and identify a UXO for clearance. Equipping the RECORM with a more sophisticated sensory package including magnetic, chemical and other sensors would make this asset too expensive to risk in a pickup operation. However, combining RECORM with cheap small robotic vehicles that could pick up the UXO and carry away ("PUCA"), or place charges for a "Blow In Place" ("BIP") clearance, is seen to provide an effective mix of capabilities; keeping the human element and high cost assets removed from the high risk areas.

The best way to combine assets and develop new clearance techniques is not yet defined. Realistic simulation studies must be conducted as an aid to establish clearance effectiveness with several schemes; this work describes just one possible scenario, described in detail in Chapter III.

In Chapter IV, search effectiveness is described from a theoretical view in terms of the two general types of search; exhaustive (a directed ladder search), and random searching. Scenario results are given in the remaining sections of the work. The main issues addressed herein are to:

1. Examine whether or not a specific search scenario approximates the theoretical random search clearance performance exponential curve,

2. Examine what impact the ability of a vehicle to accurately steer (maintain a reasonably accurate heading and position) has on clearance performance,

3. Examine to what degree obstacle avoidance, vehicle to vehicle avoidance, and vehicle transit to a disposal site while searching all have on clearance performance.

The overall thrust of this work is to study the relative merits of conducting either an exhaustive search, or a random search, for a fleet of autonomous vehicles in a range clearance scenario. It is generally recognized that in order to conduct an exhaustive search (such as a typical ladder pattern), the vehicle must be capable of fairly precise navigation. Navigation precision is necessary so that the position of the vehicle during search can be assured. If a vehicle is equipped with a precise navigation capability, exhaustive search performance in a uniformly distributed field of UXO can be expected to increase linearly with time. In other words, the clearance resulting from a ladder search with perfect navigation would result in a linearly increasing number of targets cleared versus time.

If a vehicle has no such precise navigation capability, its search performance can be expected to degrade to at least random search performance, which can be modeled as a growing exponential curve. A key concern of this work is to try to discover the relationship between the ability to navigate, and the clearance that results, for the particular scenario examined. Another concern is to determine the effectiveness of a fleet of robotic vehicles performing a pick up and carry away operation.

II. CURRENT TECHNOLOGY IN AUTONOMOUS LAND VEHICLES

A. HISTORY

Efforts toward the design and manufacture of autonomous robotic vehicles date back decades, but have increased recently with the increase in processing power of small embedded computers. Tracked vehicles have had many military uses in the form of tanks and personnel carriers. Tracks have been the mobility driver of choice whenever navigation over rough soft terrain is required. Walking machines, on the other hand, have the advantage of a smaller footprint, giving more local pressure for the same weight vehicle and better traction in soft ground. This is because the walking motion puts weight on the driving leg and increases available frictional shear loads. There is also less terrain area touched and damaged with walking machines. It is a natural then to look for walking machines to perform searches of ground terrain with mines or UXO present.

Walking machines for outdoor use go back to the early 1960's with the Exoskeleton work at General Electric in support of Moon missions funded by NASA. Later, the Adaptive Suspension Vehicle at Ohio State University was developed over several years [Ref. 1] using a hexapod machine with a double tripod gait and rule based control of motion coordination [Ref. 2]. Recently, an underwater walking machine has been built and operated in Japan, called the AQUAROBOT [Ref. 3]. This is a hexapod machine with omnidirectional response to heading commands, that has a sensor boom that can be used to scan terrain around the vehicle. It is this machine that has formed the basis of the simulator development for NAVEODTECHDIV [Ref. 4].

B. CURRENT TECHNOLOGY

Currently funded by efforts at ARPA, NASA and the Navy, several new concepts are being explored for search vehicles. They cover land, and shallow water surf zone areas and

can be divided into wheeled, tracked and walking types, depending on the propulsion method used. They may also be divided into the terrain or intended operational area, such as land based vehicles or surf zone based vehicles.

1. Land Based Vehicles

Examples of wheeled ground vehicles include the "RECORM" vehicle, manufactured by the Navy's EODTECHDIV, and the Micro-rover series, manufactured by Draper Laboratory. The "RECORM" (Remote Controlled Reconnaissance Monitor), shown in Figure 2.1 , is designed to provide remote monitoring capability or site survey of hazardous environments. It can be controlled by optic fiber or RF link. Also shown in Figure 2.1 is a prototype "BUG", a six legged vehicle with a manipulator for UXO pickup.

The Micro-rover, Figure 2.2, is a functional proof of concept vehicle manufactured by Draper Laboratories, featuring a custom robotic arm, sensors and a laser range finder. A sister vehicle, also manufactured by Draper Laboratories, is also shown in Figure 2.2. This vehicle, called the "Companion", is a testbed vehicle designed to evaluate new sensor technologies.

The Swiss Federal Institute of Technology has developed an autonomous robotic land vehicle called the "PEMEX-BE" (PErsonal Mine EXplorer). This vehicle, shown in Figure 2.3, is a very simple, light vehicle, equipped with a sensor on an arm which is connected to the wheeled control package. Direct current motors operate large wheels in alternate steps, such that a sweeping motion of the sensor arm is achieved.

2. Surf Zone Based Vehicles

An example of a tracked vehicle is the "Lemming", manufactured by Foster Miller Inc., shown in Figure 2.4. This vehicle is an example of a relatively inexpensive autonomous vehicle that carries an explosive charge, and is designed to search in a random fashion. When a suspect munition has been located by it's onboard magnetic sensor, it remains adjacent to the weapon, to be command detonated at a later time. The vehicle has two tactile sensors mounted on the front left and right sides which are used to detect objects. Based on

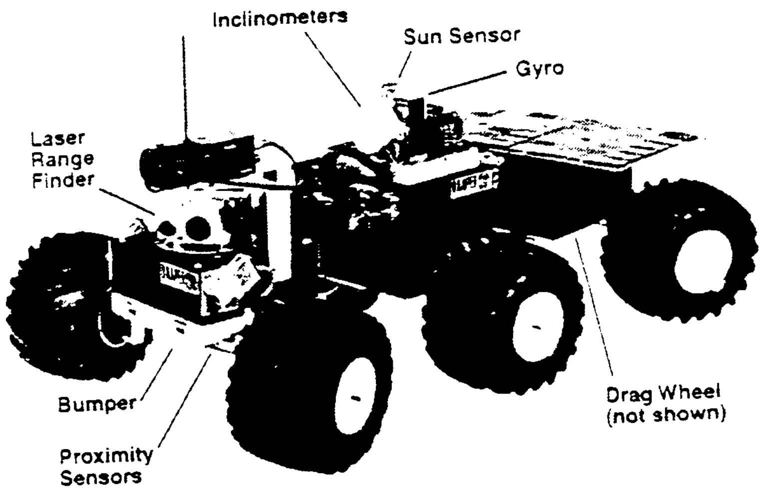
the vibration signature from the tactile sensing, a classification is made in order to distinguish rock, plastic and metallic surfaces [Ref. 5].

Examples of walking machines are from IS Robotics, Inc., and K2T. Figure 2.5 shows the "Mite" from IS Robotics, an example of a relatively inexpensive walking machine. The "Mite" is designed to operate in the surf zone, with a view to the detection of metallic objects, and operates by locating itself next to the UXO, to await a later command detonation.

Figure 2.6 is a graphical rendering of a design offered by K2T, which shows more clearly the articulated linkage associated with the walking machine's legs. Again, the function of the machine would be to operate in the shallow water surf zone and seek minelike targets.

Figure 2.7 shows a hexapod underwater walking machine called the "AQUAROBOT", [Ref. 3], which has been designed and built by the Japanese Port Harbor Authority to survey inshore underwater rock structures. A miniature version of this machine was used in the initial development of the graphics based simulator described in [Ref. 4].

Figure 2.1 NAVEODTECHDIV RECORM Vehicle and "BUG"



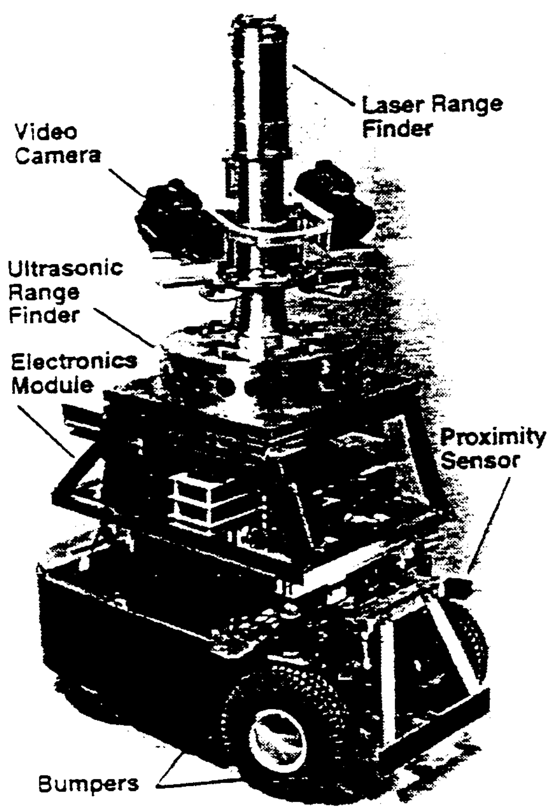


Figure 2.2 Draper Laboratory "Micro-rover" and "Companion" Testbed Vehicles

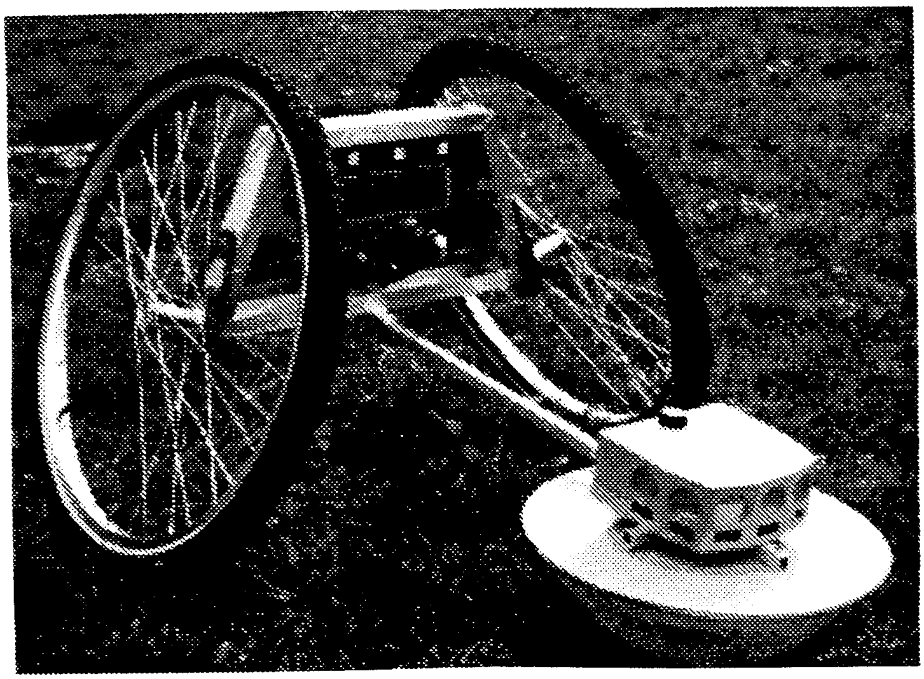


Figure 2.3 SWISS Federal Institute of Technology "PEMEX-BE" Vehicle

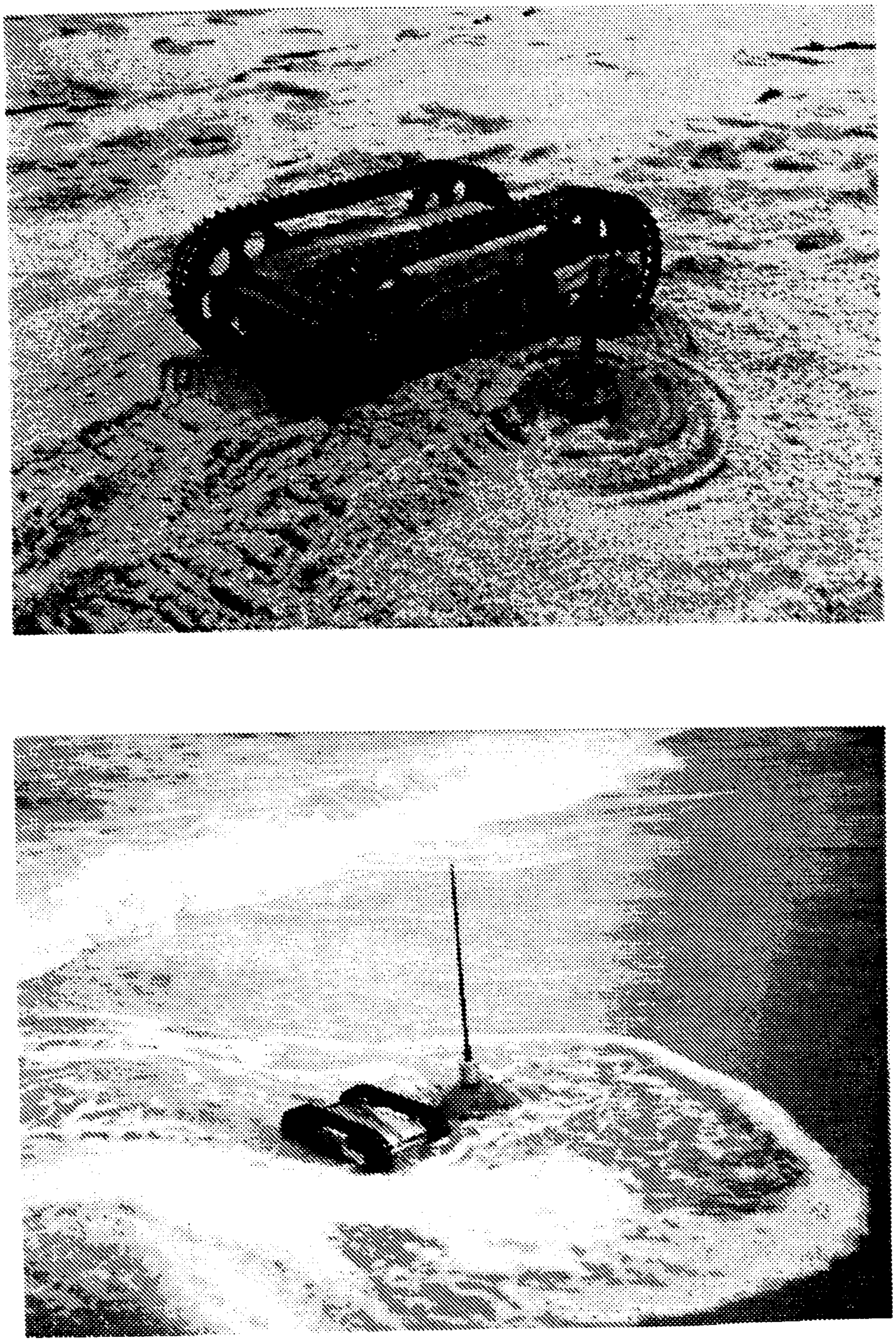


Figure 2.4 Foster Miller Inc. "LEMMING" Vehicle

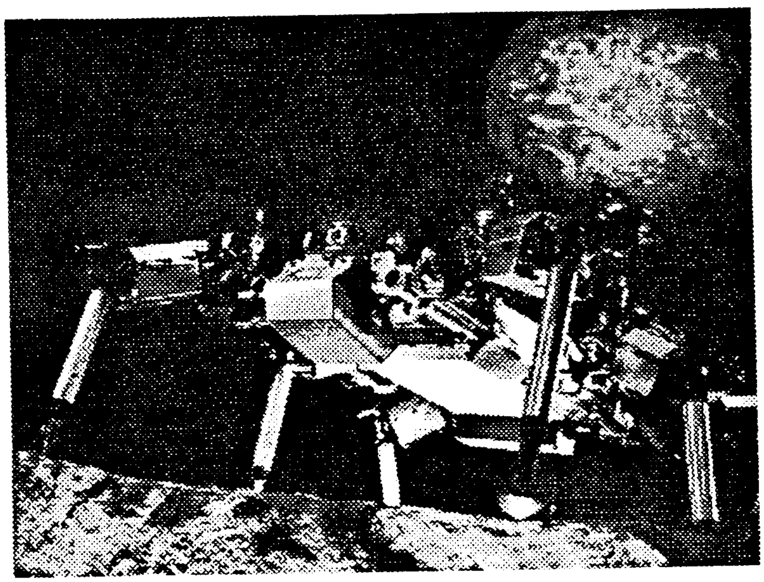


Figure 2.5 IS Robotics "MITE" Autonomous Vehicle

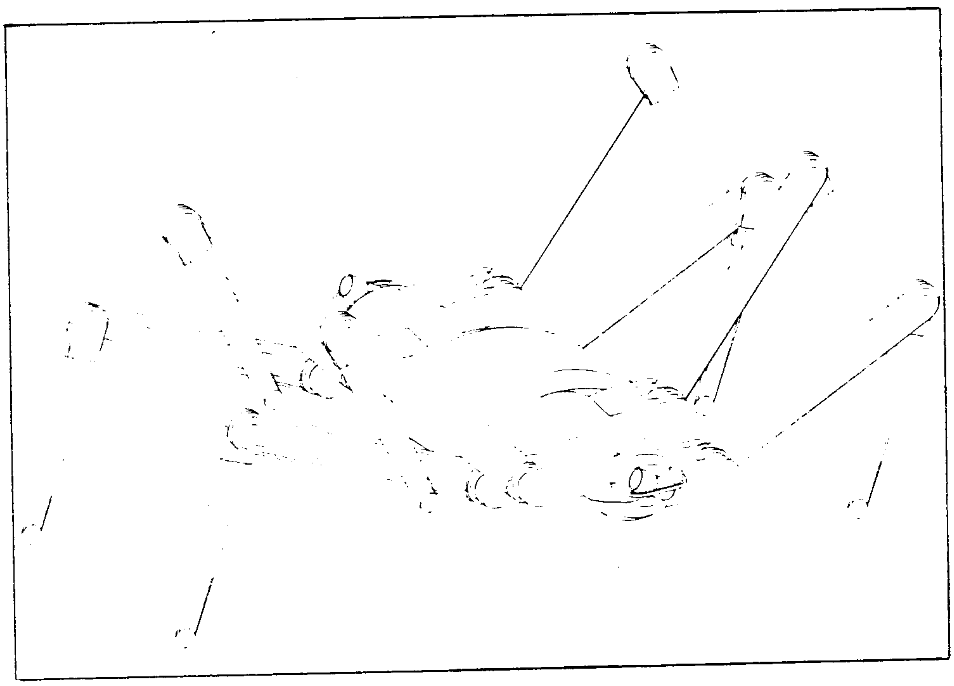


Figure 2.6 K2T Walking Machine: Design Concept

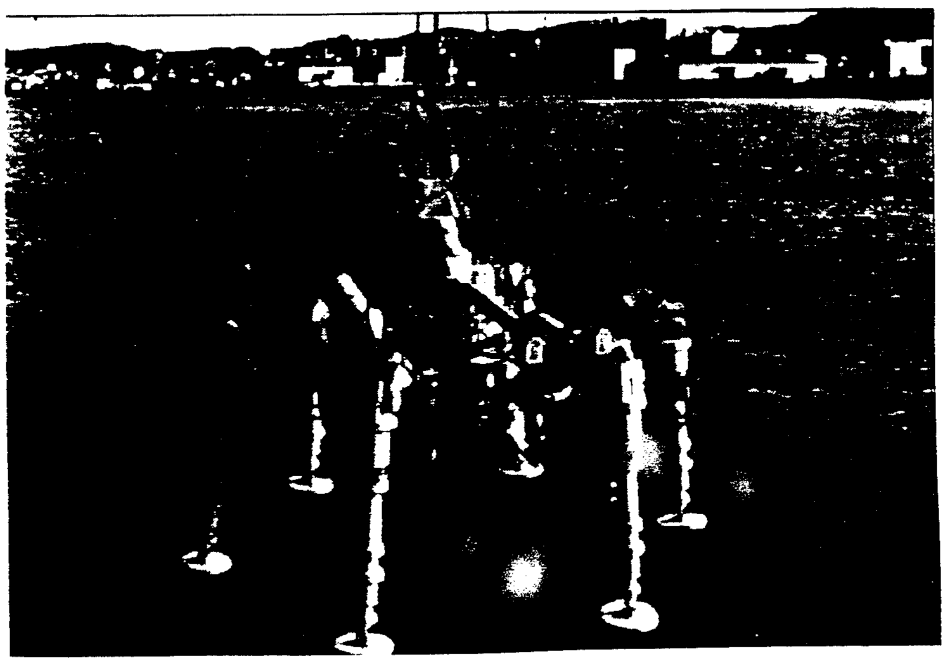


Figure 2.7 "AQUAROBOT"

III. CLEARANCE METHODS

A. SEARCH SCENARIO

1. Current Procedures using EOD Personnel

Current procedures for handling unexploded ordnance (UXO) in a range remediation environment involve a squad of personnel that slowly sweep through an area, and then having identified the suspect UXO's, proceed with defusing, or Blow-in-place ("BIP") operations. Pick up and carry away ("PUCA") operations are also conducted, although the hazard to personnel is higher if the ordnance is physically disturbed. A typical range clearance scenario for EOD might involve 8-10 personnel on a search line for several days. A recent actual EOD scenario had 10 personnel on scene for 6 hours/day, for 5 days, resulting in an estimated 90% clearance of a 3000x2000m area (3000 submunitions cleared).

2. Scenario with Small Robotics

This work focuses on the performance of a particular search scenario for autonomous land vehicles. The NAVEODTECHDIV is developing a Basic Unexploded Ordnance (UXO) Gathering System (BUGS), in order to evaluate the effectiveness of small robotic vehicles in a range remediation environment. Specifically, this work examines a scenario with the following general provisions, later identified in detail in Chapter V.

The general scenario proceeds on the assumption that the targets have been marked for recovery and disposal, by a pre-survey using a highly capable robot, or by the use of manned squads, who would simply identify suspected unexploded ordnance and mark it with some sort of acoustic or radio frequency (RF) pinger, without picking up or otherwise disturbing the ordnance.Thus, by either mechanism, the higher density areas have been identified, and the UXO's have been marked with some sort of acoustic or RF pinger that the search vehicles can identify.

One of the key requirements of small robotics systems is low cost. In order to avoid the use of a complex (i.e. expensive) navigation and control system, a relatively simple, yet effective steering system is proposed. Vehicles would steer with a rudimentary compass, resulting in essentially random steering in the search area. Coarse, random steering would then imply the need for containment in the field. A proposal for vehicle containment is made herein for a simple, commercially available pet-restraint system (discussed below). The essentially random steering is obtained by formulating the steering command heading to each vehicle from the sum of a nominal steering basis, and a periodic randomized component.

This analysis was originally conducted for a walking machine class of vehicle, however the results are nonspecific with regard to the vehicles' means of propulsion. In other words, the vehicles could be either walking machines, or tracked vehicles. The analyses herein would apply to either, provided that the velocity were the same.

B. SEARCH AREA BOUNDARIES

To bound vehicles following a random walk steering law, the area to be cleared is encircled with a barrier mechanism, whose function would be to contain the search vehicles. This study proposes the use of a very simple, commercially available pet-restraint system. There are several companies that manufacture these systems, that operate by either a low frequency (~600 Khz) AM signal, or an acoustic beacon. These systems are described in Appendix (A). Regardless of the signal, the intent of these systems as manufactured is to keep a pet in a desired area. The pet wears a collar that will first alert with an audible tone when the pet strays near the "invisible fence", and then if the pet does not turn around, receives a low level electric shock via probes on the collar. The use of such a simple system would allow the vehicles to sense when they are near the periphery of the area, and by triggering a change to the steering heading basis, turn back into the desired area. The "RECORM" vehicle could be equipped to lay down the "restraint" wire on the periphery of the area. In addition, the "RECORM" vehicle would place a pinger with a unique RF

frequency in the center of the field, that would serve as the homing signal for the area's dropoff zone. These functions are considered to lie reasonably within the capability of such a vehicle, as each search team might be equipped with one or two such high-end (more capable, and costly) vehicles.

The low cost walking or tracked vehicles are then deployed in the search area. Again, this work does not consider the vehicles specific means of locomotion (walking or tracked), except as it would relate to search velocity, as the focus of this analysis is upon the systems search performance. Indeed, search velocity will be shown to have a direct impact on clearance performance (time to achieve some desired degree of clearance).

C. TARGET ACQUISITION AND CLEARANCE

As the lower cost vehicles move into the field, lacking onboard precise navigation capability, and steering with a fairly rudimentary compass, the vehicles are expected to wander, resulting in search performance that is no better, and generally somewhat less, than the performance expected for a purely random search. In the scenario examined, the coarse steering system allows the vehicles to wander essentially at random in the field. As the vehicles detect a target via the pinger placed earlier, they acquire and home in on the target, and pick it up. After picking up the UXO, the vehicle changes it's basis heading in order to home on the signal of the master pinger placed earlier at the delivery point, where the targets are deposited for ultimate disposal. Once the vehicles drop off their targets in the disposal area, they are then free to return to the field to continue searching. "Clearance" of the target in the simulation is registered when then target is brought to the dropoff area; although it is recognized that the unexploded ordnance will only truly be "cleared" when the ordnance is properly defused or blown in place by qualified personnel. The simulation allows for each vehicle to carry one UXO.

The clearance performance of a number of vehicles can be expected to progress in time at an exponentially decreasing rate, as generally expected from search theory, and as

actually observed from the simulation. After sufficient time has elapsed such that the expected clearance levels are at some designated percentage (say 95%) of total, the vehicles are collected, and moved to a new subarea, where unexploded ordnance again has been "pre-marked by either a "RECORM"-like vehicle or manned squads. The gathered UXO's are now centralized, and can be destroyed together in place.

D. OBSTACLE AVOIDANCE AND DETECTION SENSORS

The search vehicles would require the ability to detect and avoid obstacles through some sensor system. Obstacles could be natural vegetation, irregular terrain features, rocks, possibly other vehicles in the field, or even as yet undicovered targets, if the vehicle is transiting to the center dropoff area burdened with its own target. A simple obstacle avoidance sensor might be a tactile sensor, that could discriminate between rocks, bushes, targets and other naturally occuring terrain features. Vehicles could avoid one another with a tactile sensor, or even a simple low power RF or acoustic beacon that they could recognize, one vehicle to the other.

The subject of the target sensor system, it's characterization and capability (search width), obviously have a significant impact on the search performance of the vehicles. Typical target sensor systems might include tactile, magnetic, laser, or acoustic sensors, and are not modeled here except through the specification of a detection range.

E. GENERAL SCENARIO PARAMETERS

The parameters chosen to evaluate system effectiveness are summarized in the following table.

Area	60x60 m (3600m2)
Number of Searchers	5
Search Velocity	0.2 m/sec
Random Component of Steering Error	+/- 90 Degrees, @5m, random selection
Target Handling	Carry to Center for Disposal

Table 3.1 General Search Scenario Parameters

IV. SEARCH EFFECTIVENESS

A. SEARCH THEORY

Search theory is a well studied area of interest to the military, particularly in the Undersea Warfare arena. Washburn [Ref. 6] provides an excellent treatment of both the exhaustive and random search problem, and discusses models that apply to both situations. Exhaustive searching in a fixed area is generally superior to random searching, provided that the exhaustive searcher has the requisite navigation equipment installed, so that it's position and steering can be assured to a very high degree. Figure 4.1, based on [Ref. 7], shows that for an exhaustive search, clearance performance, measured as rate of target detection, increases linearly with time, with a clearance rate proportional to the area target density. Under the assumption that the UXO are statistically uniformly distributed and independent from run to run, the average rate of detection, dq/dt, is given by [Ref. 6],

$$\frac{dq}{dt} = \frac{U_o (2r) N_v N_o}{A} \qquad (4.1)$$

where q(t) represents the expected value of the number of UXO's cleared up to time t, U_o is the search speed, r is the sensor radius of detection, N_v is the number of vehicles, N_o is the initial number of targets, and A is the search area. Since all terms are constants for a particular scenario, the solution of Equation 4.1 is linear,

$$q(t) = K\,t, \quad \text{for} \quad 0 < q(t) < N_o \qquad (4.2)$$

and

$$q(t) = N_o, \quad t > N_o / K \qquad (4.3)$$

where $K = U_o\,(2r)\,N_v\,N_o / A$, the slope of the clearance vs time graph.

The time necessary for an exhaustive searcher to completely cover the search area is then T_o, where

$$T_o = \frac{A}{U_o 2rN_v} = \frac{N_o}{K} \tag{4.4}$$

For a random search, however, the clearance performance curve is lower, and depends on the number of UXO's already cleared. Mean target density is reduced as targets are cleared from the field. For random searching, clearance rate is modeled by,

$$\frac{dq}{dt} = U_o 2rN_v \frac{(N_o - q(t))}{A} \tag{4.5}$$

Solving this equation for q(t) yields:

$$q(t) = N_o (1 - \exp(-\alpha t)) \tag{4.6}$$

where

$$\alpha = U_o (2r) N_v / A \tag{4.7}$$

and is called the *characteristic clearance rate,* with $\alpha = 1 / T_o$.

Thus, where the exhaustive searcher (with perfect navigation) achieves complete coverage in time $T_o = A \;/\; (U_o\,(2r)\, N_v)$, the random searcher clears (1 - exp (- 1)) of its targets in the same amount of time, or 63.2 % of targets cleared. Also, to clear to 90%, 95%, and 98% of N_o, the times $t_{.90}$, $t_{.95}$, and $t_{.98}$ are given in the table below.

$t_{.63}$	$1 \quad T_o$
$t_{.90}$	$2.3 \quad T_o$
t_{95}	$2.99\ T_o$
t_{98}	$3.91\ T_o$

Table 4.1 Times to Clear to Various Clearance Percentages

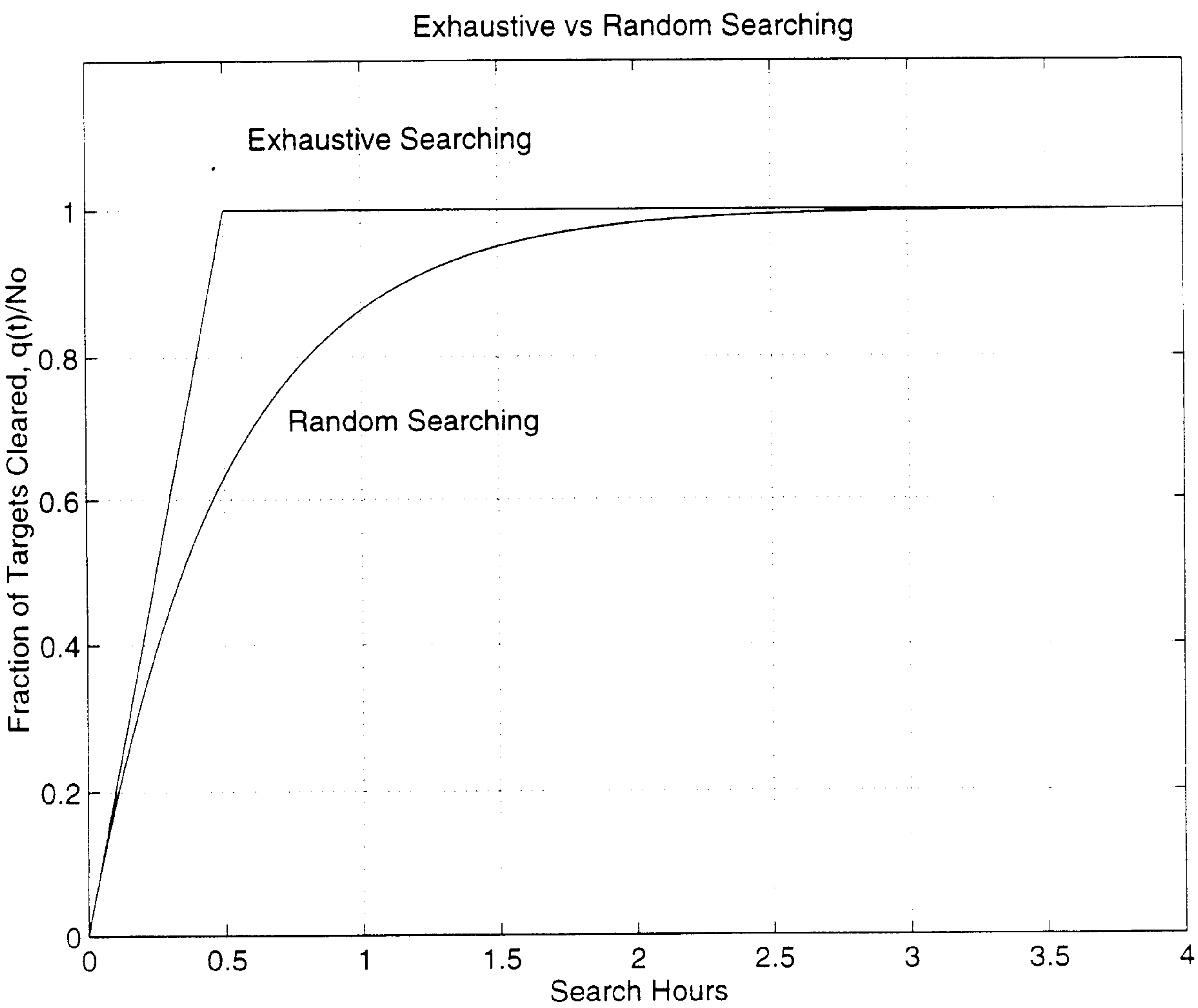


Figure 4.1 Exhaustive vs Random Searching

V. SIMULATIONS

A. SIMULATION PARAMETER DEFINITIONS, GENERAL

In the results that follow, many simulations have been made, generating a large amount of data. In discussion of this data, a common nomenclature has been used. Values for these parameters are changeable in the simulator code, although a common set of values for the clearance scenario studied are presented.

Parameter	**Definition**
N_v	Number of Vehicles
N_s	Number of steps
N_o	Initial number of targets
N_{obst}	Number of obstacles
U_o	Vehicle velocity
dt	Step size
Raddetect	Radius of detection
P_d	Probability of Detection
q	Clearance, defined as Number of targets cleared
α	Characteristic clearance rate
ψ_{basis}	Used to define the predominant direction of search, or to "home" to the dropoff area
ψ_{rand}	The random heading error introduced, added to the basis

B. SCENARIO PARAMETERS: RANDOM SEARCH, WITH OBSTACLE AVOIDANCE AND DISPOSAL TRANSIT

The search area is defined as a 60m x 60 m (3600 m^2) area, with a target (UXO) density of .02 (72 targets per 3600 m^2). This value was used as representative of a typical ordnance range UXO density, from discussions with NAVEODTECHDIV. Targets are placed using a uniform probability distribution in both coordinate directions over the search area. Targets are not placed in an area in the center of the search area, reserved for the dropoff area. This is considered reasonable, since a "RECORM" like vehicle would have the capability to sanitize an area, or at least survey a small area within the search area that could be used for disposal. Vehicle velocity is assumed to be 0.2 m/sec (20 cm/sec). The number of vehicles (searchers) is 5, and the obstacle density is assumed to be .02 (72 obstacles per 3600 m^2). The UXO sensor for this analysis is asssumed to be of the "Cookie Cutter" type, with a probability of detection of 1.0. The detection radius is assumed to be 1.0 m, meaning that any target that is encountered within this radius is considered acquired. Simulation software used is Matlab. "For" loops are used, with position updates and check of detection radius (all vehicles to all targets) for each position. The primary 'm file' used for simulation result generation is given in Appendix C.

C. VEHICLE CONTROL FEATURES SIMULATED

1. Heading Control

The Global coordinate frame used in the simulation has the Y axis taken as the horizontal, and the X axis taken as the vertical. The 5 vehicles start on the Y axis (south boundary) of a search subarea, evenly dispersed from 0-60 m. Initial starting headings are then given by a predominant direction (basis) equal to zero, to which is added a random angle from plus 90 to minus 90 degrees on either side of the nominal "north" (X) direction. The vehicles travel on randomly selected headings in the "predominant" direction, and change to new random headings every 5m.

The steering law can then be considered to be,

$$\psi_{command} = \psi_{basis} + \psi_{rand} \tag{5.1}$$

This steering law is intended to represent the steering that will result from the vehicles rather poor ability to steer and maintain position and desired track in a sometimes very rough terrain and environment.

2. Boundary Reflection

The predominant direction of search (or transit to disposal site) is referred to as the vehicle's "basis". If any vehicle at any time calculates it's next position to be outside of the search area, it is made to adopt a new basis away from (perpendicular to) the boundary encountered. Thus, although the initial basis is in the X direction, any subsequent encounters with any of the four boundaries results in a reflection from the boundary at that point in a direction perpendicular to that boundary. Simulation run time is determined by the number of steps taken in the simulation.

3. Obstacle Avoidance Logic

Built into the vehicle control function is the assumption of an obstacle detection sensor that would trigger an avoidance manuever capability. Detection capability for another vehicle, obstacles such as rocks or vegetation, or other UXO's is assumed. When a vehicle encounters an obstacle while searching (within 1.0 m), it makes a turn to starboard (right) by approximately 90 degrees (actually 100 degrees). The vehicle continues to run in the turned direction for the remainder of a counter that runs and resets continuously. After the counter runs out, the vehicle picks another random heading in the previous predominant direction. The duration of the counter is 5 meters during searching, and 2 meters during homing. In other words, while searching, the maximum distance a vehicle could travel during obstacle avoidance is 5 meters (2.5 meters average) while searching, and 2 meters (1 meter average) during homing. This is done to try to allow for a reasonable obstacle avoidance distance, and

yet minimize the average amount of time the vehicles spend pointed away from the disposal site while trying to "home". Additionally, if while homing, the vehicle encounters another target that has not yet been acquired, it treats it as an obstacle, and avoids it according to the same rules above.

When any vehicle comes within the detection range of any other vehicle (1.0 m), both vehicles make an approximately 90 degree turn to starboard (100 degrees). They continue to run along that heading until their original basis and heading are reestablished by a 5 meter counter (while searching), or a 2 meter counter (while homing) that run and reset continuously.

4. Target Acquisition and Disposal

If any UXO lies within the detection radius of any vehicle, that UXO is assumed to be acquired by that particular vehicle. Following that action, the vehicle is assumed to change it's heading control basis to a homing basis, and calculates a heading to the dropoff area. This simulates the vehicle having acquired the master pinger homing signal from the master pinger in the center of the dropoff area. In the homing mode of control, it is assumed that a sensor would be available onboard to determine direction to the source of the master pinger - a technique very commonly used with underwater acoustic pingers and land based radio frequency pingers. The vehicle then navigates to the dropoff area, avoiding both obstacles and other not yet acquired targets while enroute to the disposal site. When the vehicle enters the dropoff area, it drops off it's UXO, turns around, and re-enters the field to continue searching. When the UXO has been "gathered" into the center dropoff area for ultimate disposal, the clearance counter is incremented. Although for the purposes of the simulation the clearance of that UXO has been registered, it is recognized that the UXO will only properly be cleared when it is blown in place or otherwise properly neutralized .

D. VEHICLE CONTROL FEATURES FOR STEERING ERROR VS CLEARANCE ANALYSIS

As in the search scenario above, 5 vehicles start on the Y axis, dispersed in a pattern that would allow the complete (all targets acquired) coverage of the field, given perfect steering (that is, random component of steering is zero). Initial starting headings are random angles from plus to minus degrees, selected from 0 to 30 degrees, on either side of the nominal "north" (X) direction. Vehicles retain their headings for 5m, as in the search scenario, where a new random component is added to the basis heading. The vehicles travel to the other end of the field, turn west for 2 meters, and then turn south for the return run. Upon reaching the south boundary (X=0), the vehicles turn west again, travel for 2 meters, and then head north for another segment. In the 60x60m scenario, 1800 seconds (1/2 hour) of vehicle run time is needed to attain complete coverage, at least for the perfect steering case.

The target population (again, 72) is created using a uniform random distribution. Because the purpose of this analysis was to simply examine the effects of increased steering error on clearance performance, no obstacles were set. The original 60x60 meter area scenario was therefore simplified to the point that the effects of steering error alone could be seen.

Vehicles again travel with 0.2 m/sec velocity. and for each position, detection radius is checked for all vehicles to all targets at every step. If any target falls inside of the detection radius for any vehicle (1.0 m), a counter is iterated, and the target is removed from the field, preventing further acquisition by another vehicle (or possibly reacquisition by the same vehicle). Final clearance for each simulation is calculated from the ratio of targets acquired to total targets placed in the field. It is recognized that this method of "clearance" may not be completely realistic, as it provides for an essentially unlimited supply of explosive charges for each vehicle, however, again, the purpose of the analysis was to characterize the relationship between steering error and clearance.

E. PETRI NET REPRESENTATION

A recent development in discrete event systems design is the use of the Petri Net, described in detail in [Ref. 8]. A Petri Net is a graphical representation of discrete event processes, that contains the elements of places, transitions, and directed arcs joining the two. Places are depicted by circles, and transitions are depicted by bars. In general, a place can be an output place from a transition, or an input path from a transition. A place may be considered to be a state, and a transition may be considered to be the sensor or equipment action that triggers the "transition" from place to place.

The presence or absence of a "token" (dot in the center of a place) indicates whether that place is logically true, or false. In other words, the transitioning of the system state through the discrete event process is represented by the movement of tokens from place to place. This methodology has a mathematical basis in Discrete Event control system design and is convenient to show the logical basis of the search vehicles' control system.

Figure 5.1 is a Petri Net representation of the search algorithm used in this work. It can be seen that there are 5 places, and 8 transitions activated by sensor obtained signals connecting the places. Figure 5.1 gives a conceptual representation of the state transitions in the search scenario used herein.

F. GRAPHICS BASED SIMULATOR

This work was accomplished in parallel with a graphics based simulator, discussed in detail in [Ref. 7]. Figure 5.2 is a screen capture of a scene from this simulator, where a BUG delivers a UXO at the disposal point in the search area. A realistic, fully textured terrain and six degree of freedom walking machine are modeled, in order to gain a deeper understanding of the challenges surrounding the dynamics of the UXO clearance environment.

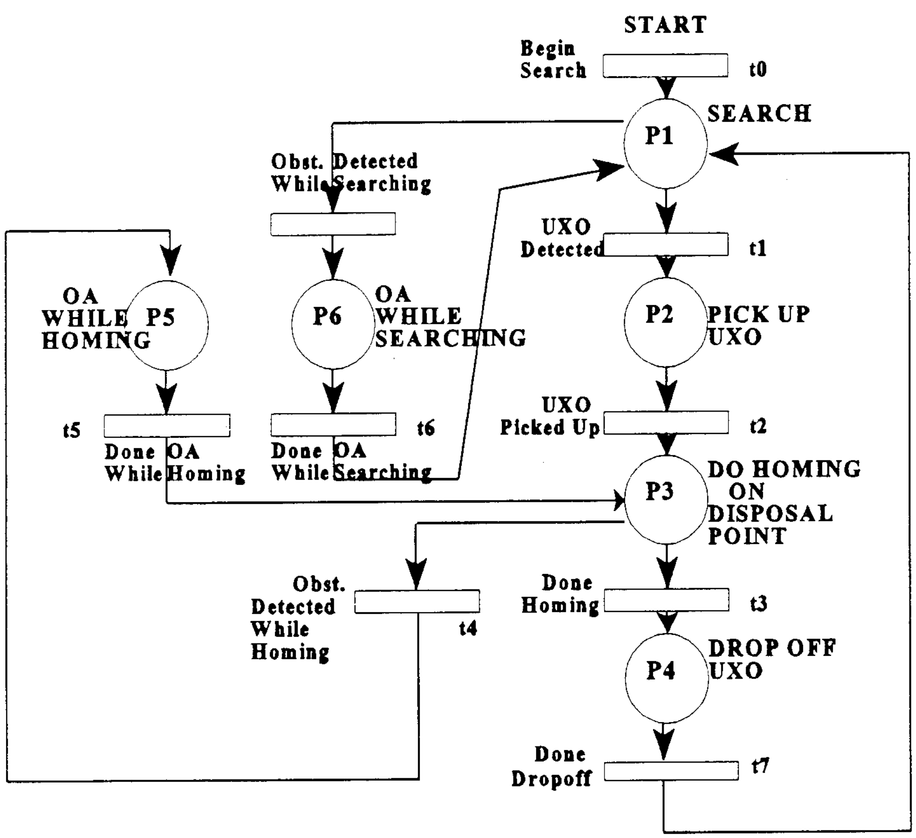


Figure 5.1 Petri Net Representation of Search Scenario

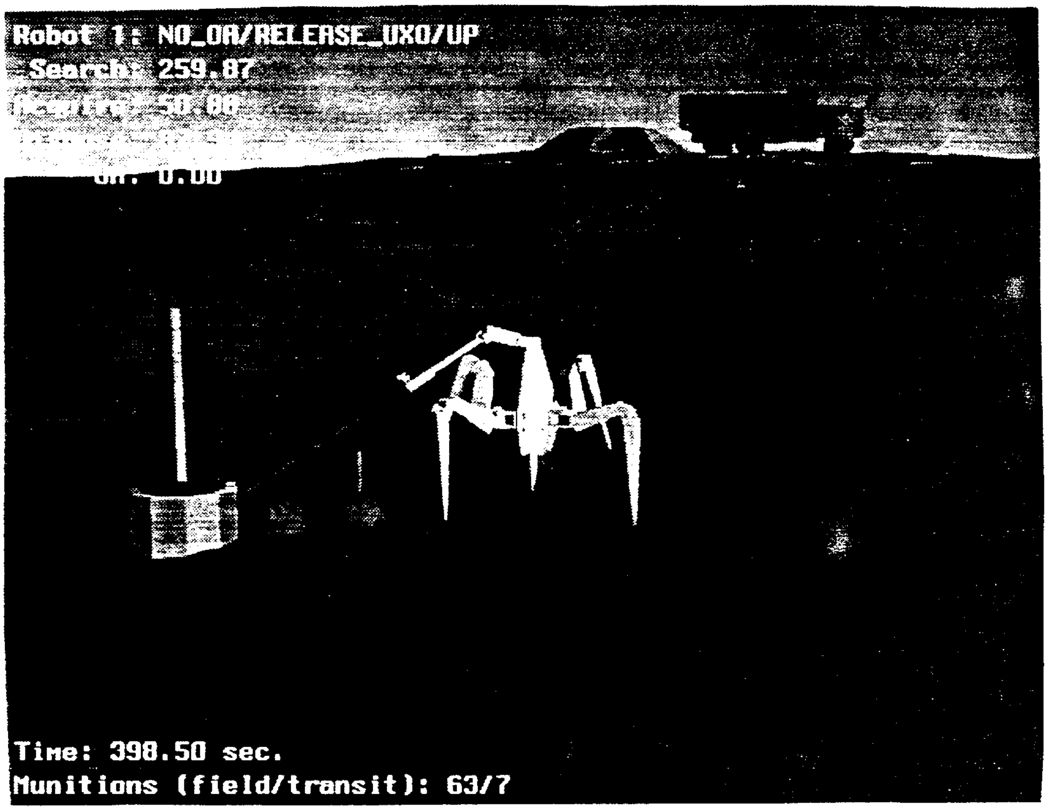


Figure 5.2 Graphics Based Simulator

VI. DISCUSSION OF RESULTS

A. GENERAL

An immediate question that arises when one considers the deployment of a number of autonomous vehicles in a two (or three) dimensional space is vehicle control. Central to the performance of vehicles in a search environment is the ability to navigate, with the attendant issues of complexity (and cost) of the control and navigation suite. In order to take advantage of the benefits that arise from exhaustive search performance (Figure 4.1), one must be willing to equip the vehicle with a precise navigation system. This of course raises the cost of the vehicle significantly. A key design decision therefore, if one intends to conduct an exhaustive search, is to equip the vehicles with a precise navigation capability, in order that the vehicles remain on their desired paths, and not wander into areas already searched, or possibly return to specific positions.

B. STEERING ERROR VS CLEARANCE

To what degree does this ability to navigate affect search performance? Or, put in more practical terms, how poorly does the steering or navigation have to be, before it no longer matters, since the performance has approached the performance of a similar system having purely random steering behavior? Figure 6.1 attempts to characterize this relationship, and was generated from 20 independent runs for each additional degree of steering error imposed beyond the perfect steering case, up to 30 degrees steering error. The simulation run time for all steering error runs was the run time that would be associated with complete coverage in an equivalent exhaustive search scenario, (1/2 hour) and 63.2% coverage in a random search scenario (again, 1/2 hour). A random steering error component was introduced every 5 meters of vehicle travel. For example, 20 degrees of steering error represents a random selection of some heading between plus and minus 20 degrees of the desired track invoked (added) every 5 meters.

The large number of simulations required approximately 20 hours of run time among 4 SGI Indy workstations, but was necessary because clearance is a statistical quantity. 20 simulations for each level of steering error gave an estimated clearance result with 19 degrees of freedom, and a relatively smooth estimate of the relationship sought.

Figure 6.1 essentially shows that as steering error approaches approximately 10 degrees, one doesn't achieve much more search performance than that of a random searcher. Comparing Figure 6.1 to Figure 6.2, which is a time averaged set of runs from a "random" search scenario using the same search parameters, one sees that at 1/2 hour of simulation (real) time, one achieves approximately 56% clearance in the random case. Figure 6.2 was generated by applying a plus or minus 90 degree steering error, every 5 meters, in the predominant search heading, and does not include obstacles or transit to a disposal point. It is revealing to note that the steering error curve is asymptotic to approximately 56%, and that Figure 6.2 shows that at the same equivalent search time (1/2 hour), approximately 55% was achieved. This shows that as steering error rises toward 10 degrees or so, clearance performance approaches that of a random search. This is a significant observation, since it shows that steering error must be relatively small, if one expects to reap the benefits of exhaustive search.

Figures 6.3, 6.4, and 6.5 show the results of three representative steering error vs clearance simulations. Shown are the tracks in the search area resulting from runs with 3, 8 and 18 degrees steering error. As the magnitude of the random component of steering error is increased, one can clearly see the large "holidays" in coverage that result, with the commensurate increased number of targets left uncleared in the field.

One simple alternative to improving search performance through improved navigation is by increasing the number of searchers. Since search performance theory generalizes when there are multiple searchers, it becomes a simple matter to simply add to a fleet of

inexpensive vehicles to increase clearance performance, by linearly increasing the exponential parameter with number of searchers added. With a large number of vehicles used in a search scenario, this might be a cheaper alternative to attempting to improve the design navigation performance of each vehicle by itself. The effect of an increased number of searchers is discussed in section F below.

C. COST OF ACHIEVING A LOW STEERING ERROR

With regard to the range clearance scenario, the more specific question then becomes: " Can an inexpensive walking (or tracked) vehicle navigate precisely enough to be able to conduct an exhaustive search? "

When one considers the terrain that the vehicles must operate on, in order to assure the heading and position of the vehicles to a high degree, the navigation and control suite becomes increasingly complex, and expensive. As shown in Appendix (B), the cost of GPS and DGPS systems are still a significant part of the Target 1K per vehicle, even in quantity. Although several commercial RF and other microwave/transponder systems are available, none of the inexpensive systems have a precision great enough to be able to allow a vehicle to reacquire a target by position information to within a meter or so. Therefore, one must conclude that at this time, it would be very difficult to manufacture an inexpensive vehicle that can search autonomously and navigate precisely.

As stated above, and as shown by Figures 6.1 and 6.2, it doesn't take very much steering error for the search performance to degrade to that of a random search. So, if one admits the cost and complexity that go with a requirement to navigate to the degree that one can get the benefits of exhaustive search, then why bother with the precise navigation at all? Why not simply equip the vehicles with a rudimentary compass, and odometer, and let them wander to the degree that the terrain allows, to be restrained only by an inexpensive periphery system such as that described in Appendix A? Since random search performance is quickly obtained unless steering is quite good, why not simply let the vehicle wander in the field,

creating a random search environment?

D. PENALTY FOR OBSTACLE AVOIDANCE AND DISPOSAL TRANSIT

1. Simulation Results

Figure 6.6 shows the results of ten simulations where 5 searchers search an assigned area with randomized steering. The simulation returns results for clearance that has an exponentially decreasing clearance rate, as might be expected from search theory. As can be seen by Figure 6.6, this was indeed observed. However, there is a penalty in clearance performance, due to the additional maneuvering required as the vehicles transit "off-line" to the center drop-off area, and conduct obstacle and vehicle to vehicle avoidance. Since for any given point in time, there is a certain percentage of searchers on average, that are essentially off-task, the performance will be commensurately lower. For this scenario, the vehicles can pick up only one UXO, although a multiple-carry scenario is certainly desirable, and will be mentioned as a scenario for future study. Since the vehicle enroute to drop-off is not searching, it represents a temporary loss in searchers for this period of time, and is further exacerbated by the maneuvering that the vehicle must do to continue to avoid obstacles, which includes avoiding targets it encounters enroute to the dropoff point.

2. Confidence Intervals

For small samples, the Student t Distribution [Ref. 9] gives a method for estimating the level of confidence in the mean. The following terms are used:

μ = The actual mean (generally unknown) of the PUCA process

$\overline{x}$ = The sample mean (from the data), and estimate of μ

σ = The actual standard deviation (also generally unknown)

S_x = The sample standard deviation (from the data), and estimate of σ

n = Number in the sample

ν = Degree of Freedom (defined as n - 1)

There will normally always be some difference between the actual mean and our estimate, and the actual standard deviation and it's estimate, and we use the confidence interval concept to describe this difference. The Student t Distribution defines a probability distribution for a variable ' t ' that relates to the degree of error between the true mean and the estimate of the mean, that is based on ν, the degree of freedom of the sample. The t distribution is given by,

$$t=\frac{\bar{x}-\mu}{S_x/\sqrt{n}} \tag{6.1}$$

For each of 10 simulation runs (n = 10), 120 data points were recorded. The Student t probability distribution associated with $\nu = 9$ degrees of freedom, lists a value for 2 sided confidence intervals, at a 95% confidence level, as 2.262.

Since the t distribution reflects a measure of the difference between the actual mean and the estimated mean, or $\bar{x} - \mu$, we may restate equation (6.1) for $\bar{x} - \mu$,

$$|\bar{x}-\mu| \leq \frac{tS_x}{\sqrt{n}} \tag{6.2}$$

$|\bar{x} - \mu|$ is a measure of the confidence we have in the estimate of the mean, and can be considered a confidence interval. The confidence interval can be added to, and subtracted from each data point mean ($\bar{x}$), and represents an outer bound where we would expect to find the true mean, at a level of confidence indicated by ' t '. These confidence intervals for a 95% level are shown on Figure 6.6 as the outer two bounding curves. These curves give an indication of the variability of the data about the calculated mean, and we can say with 95% confidence that the mean for each data point falls within these boundaries.

3. Software

The software used for the simulations is MATLAB. Simulation runs were conducted on SGI Indy computers, in recursive fashion, in order to generate multiple independent runs. The MATLAB workspace was reset for each run, ensuring independent data from run to run. It was found that the simulation ran at only a fraction of real time when 5 vehicles and 20 or 30 targets or obstacles were used. However, when the more realistic target and obstacle density was invoked (72 targets, 72 obstacles per $3600m^2$), the simulation ran at what would be only slightly faster than real time, due to the many checks for obstacle avoidance and target acquisition at each step in the simulation.

E. THE EFFECT OF AN INCREASED NUMBER OF DISPOSAL POINTS

It is reasonable to assume that clearance rate might be related to the geometry and number of disposal points provided in a fixed search subarea. For optimum locations, or increased numbers of disposal points, the amount of time the vehicles spend conducting transit to disposal area should be less, which should improve the clearance rate. Figures 6.7, 6.8 and 6.9, taken from [Ref. 7], show "BUGS" paths for three different disposal point locations, from a graphics based simulation with the same simulation parameters stated in Chapter V. Figure 6.7 is data from one disposal point in one corner, Figure 6.8 is data from one disposal point in the center, and Figure 6.9 is data from 5 disposal points (one in the center, and one in the center of each quadrant of the square). One can clearly see the attractive effect of the disposal point location.

Additionally, Figure 6.10, from [Ref. 7], shows the average percentage of time (for 5 bugs) that was devoted to search and PUCA operations, for the three scenarios mentioned above. Clearly, for 5 disposal points placed throughout the search subarea, the bugs can be seen to spend more of their time searching, and less of their time actually transiting to disposal points for target dropoff. Figure 6.11, also from [Ref. 7], represents a clearance time history for one run with 5 bugs for the three different disposal location scenarios. One can see that

the 5 disposal point scenario produces an improved clearance rate.

F. THE EFFECT OF AN INCREASED NUMBER OF SEARCHERS

The parameter α, or characteristic clearance rate, was defined in Chapter IV as,

$$\alpha = \frac{U_o(2r)N_v}{A} \tag{6.3}$$

and is a function of vehicle velocity (U_o), sensor radius of detection (r), number of vehicles (N_v), and search area (A). As an exercise to examine whether or not the parameter α would change as the number of vehicles are changed. N_v was increased from 5 to 8, and then 10, and the random search with one center disposal point scenario was re-run for these numbers of vehicles. One would expect that there would be a linear increase in α as the number of vehicles is increased. Indeed, Figure 6.12 shows roughly a linear increase in α with an increase in searchers, as,

Number of Vehicles	α	Expected Increase	Actual Increase
5	.3926	1	1
8	.6426	1.6	1.636
10	.8356	2.0	2.547

Table 6.1 Effect of Increased Number of Searchers

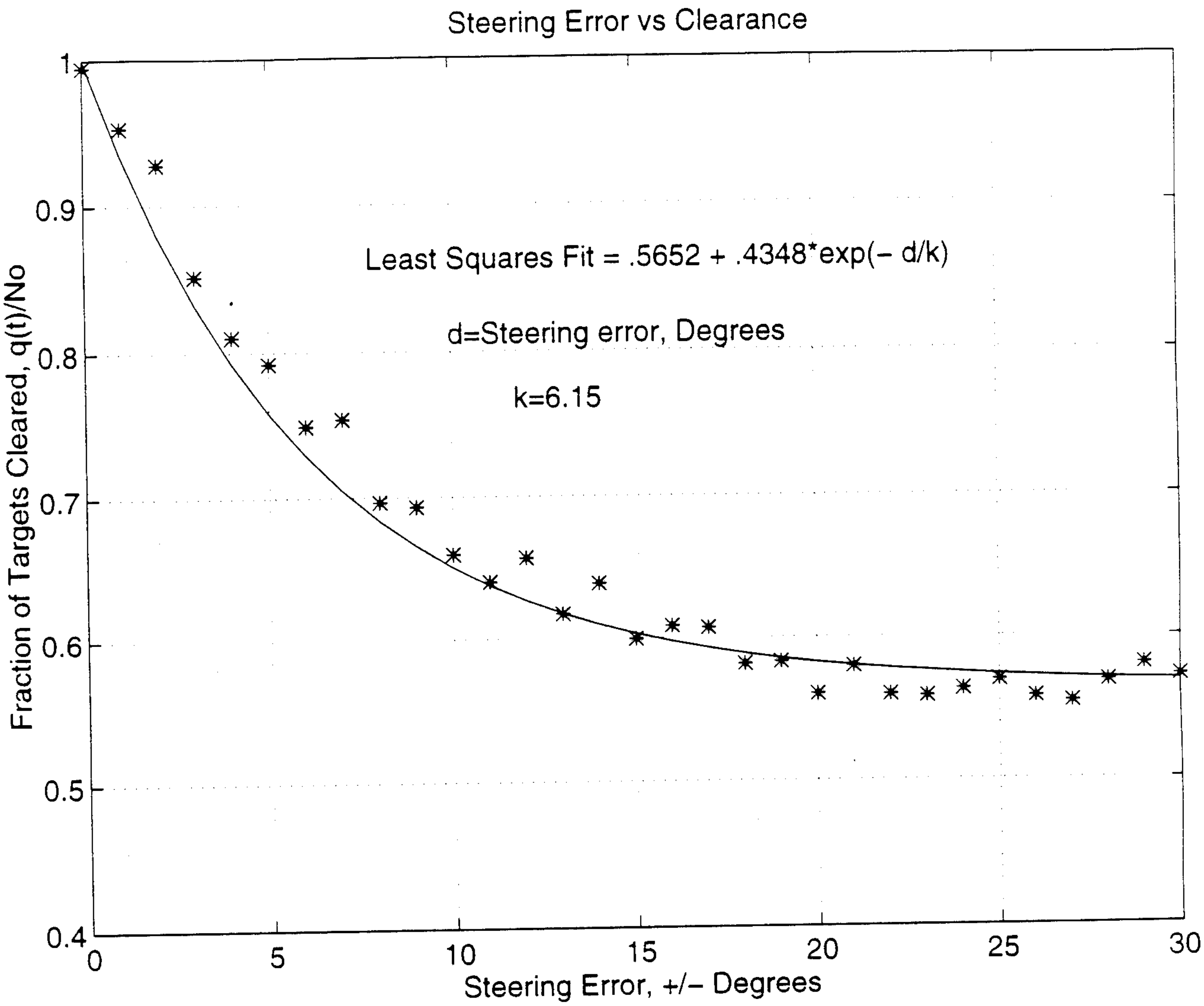


Figure 6.1 Steering Error vs Clearance

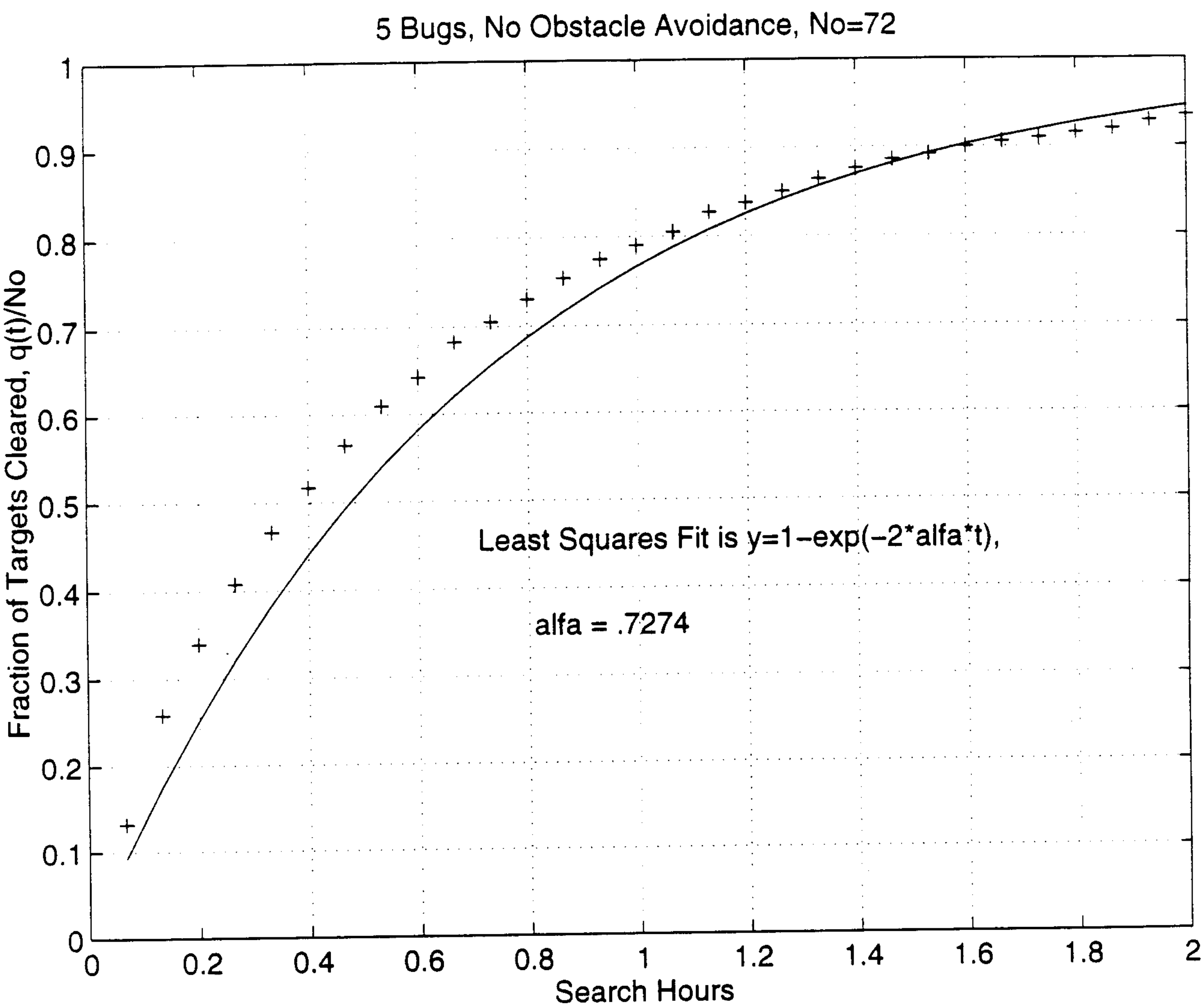


Figure 6.2 Random Searching, For Comparison

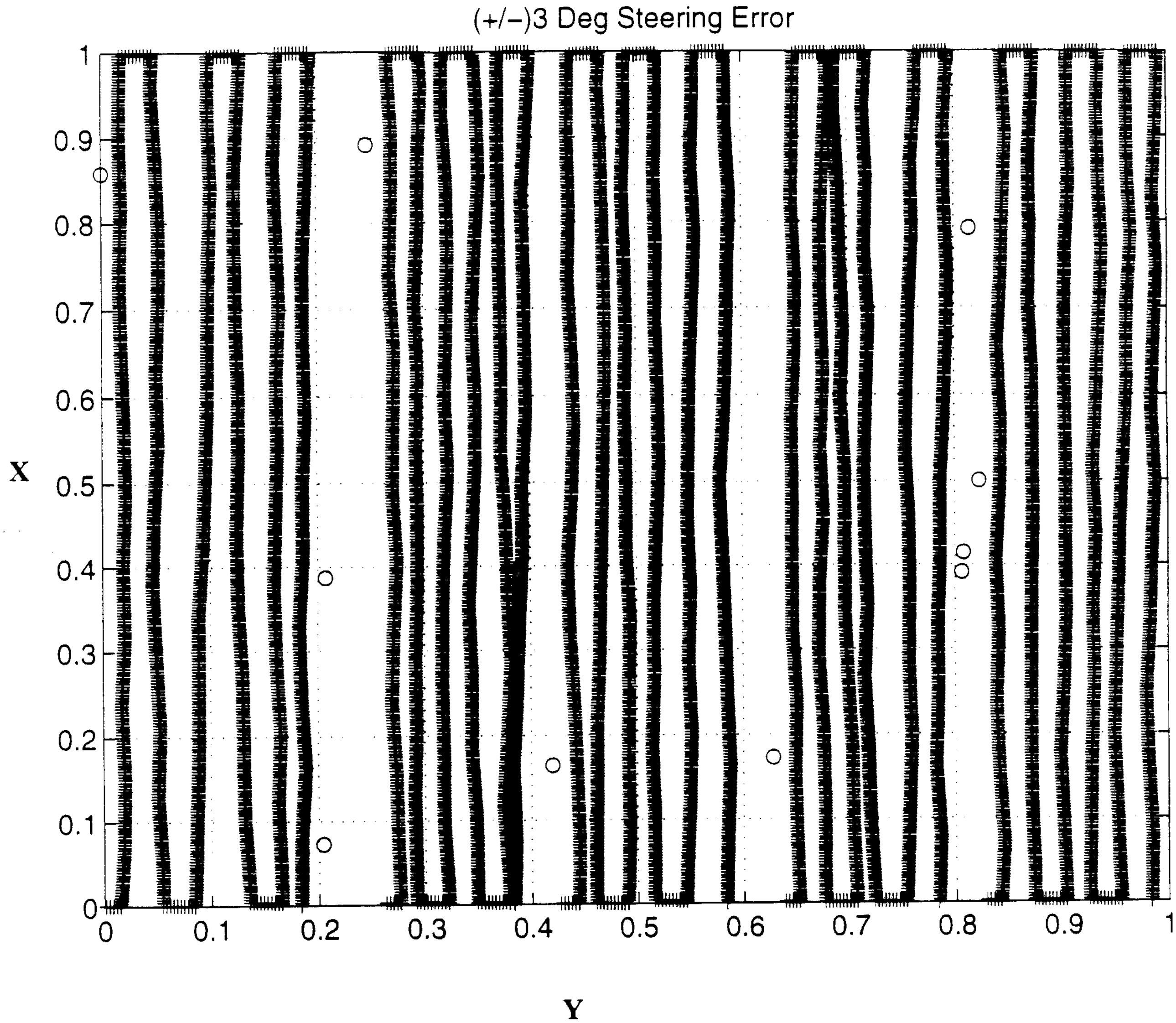


Figure 6.3 Steering Error vs Clearance, +/- 3 Degrees

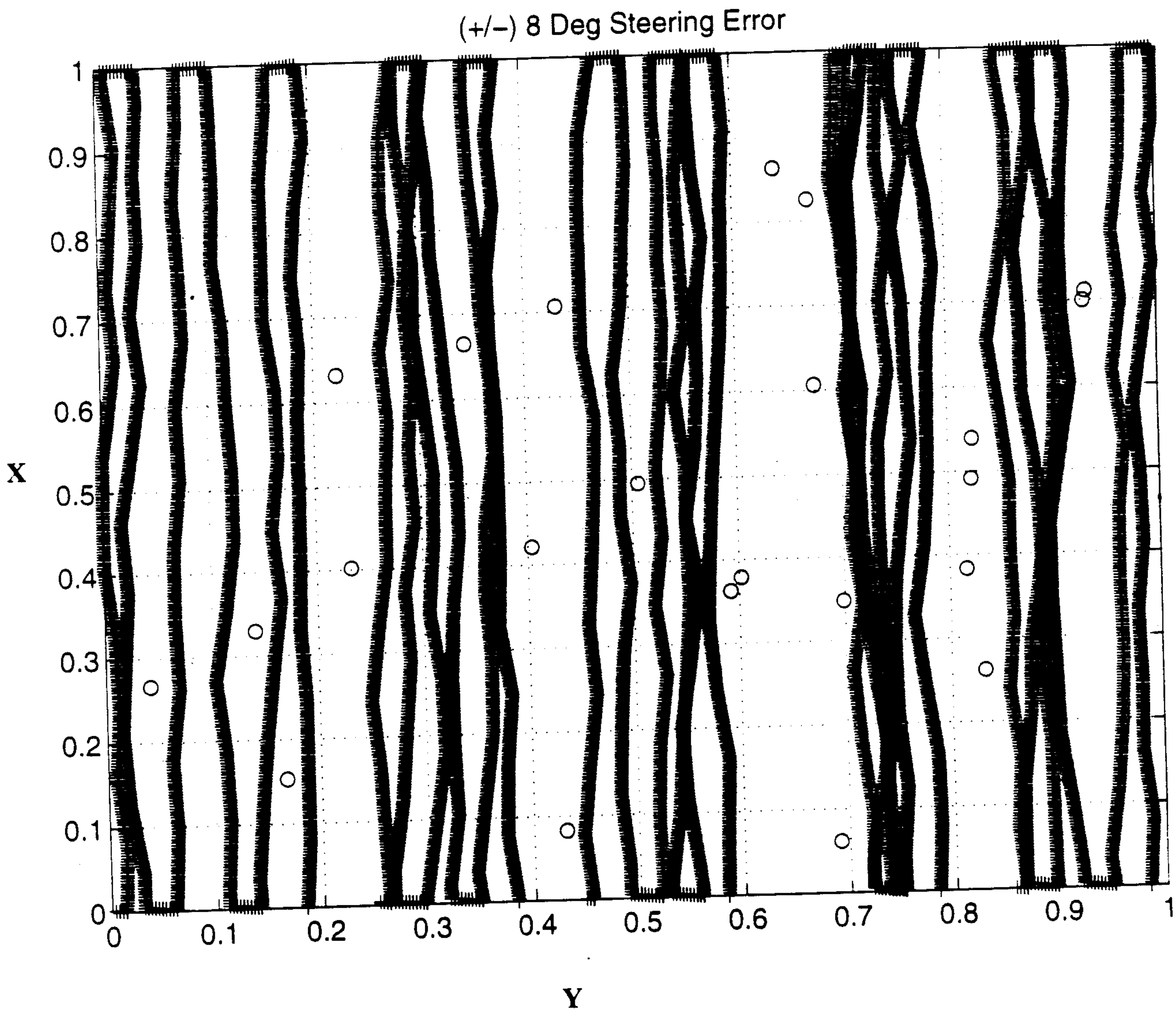


Figure 6.4 Steering Error vs Clearance, +/- 8 Degrees

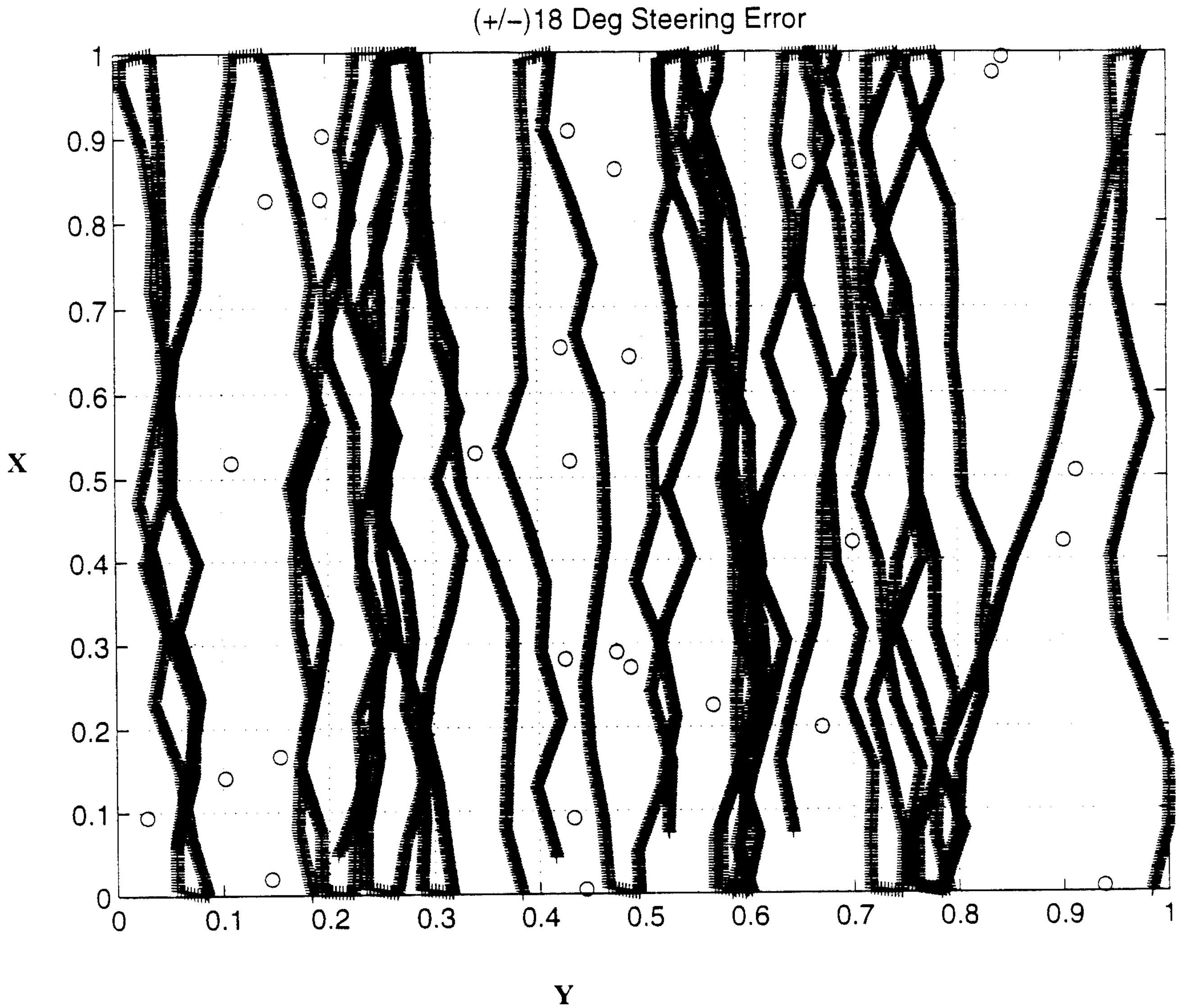


Figure 6.5 Steering Error vs Clearance, +/- 18 Degrees

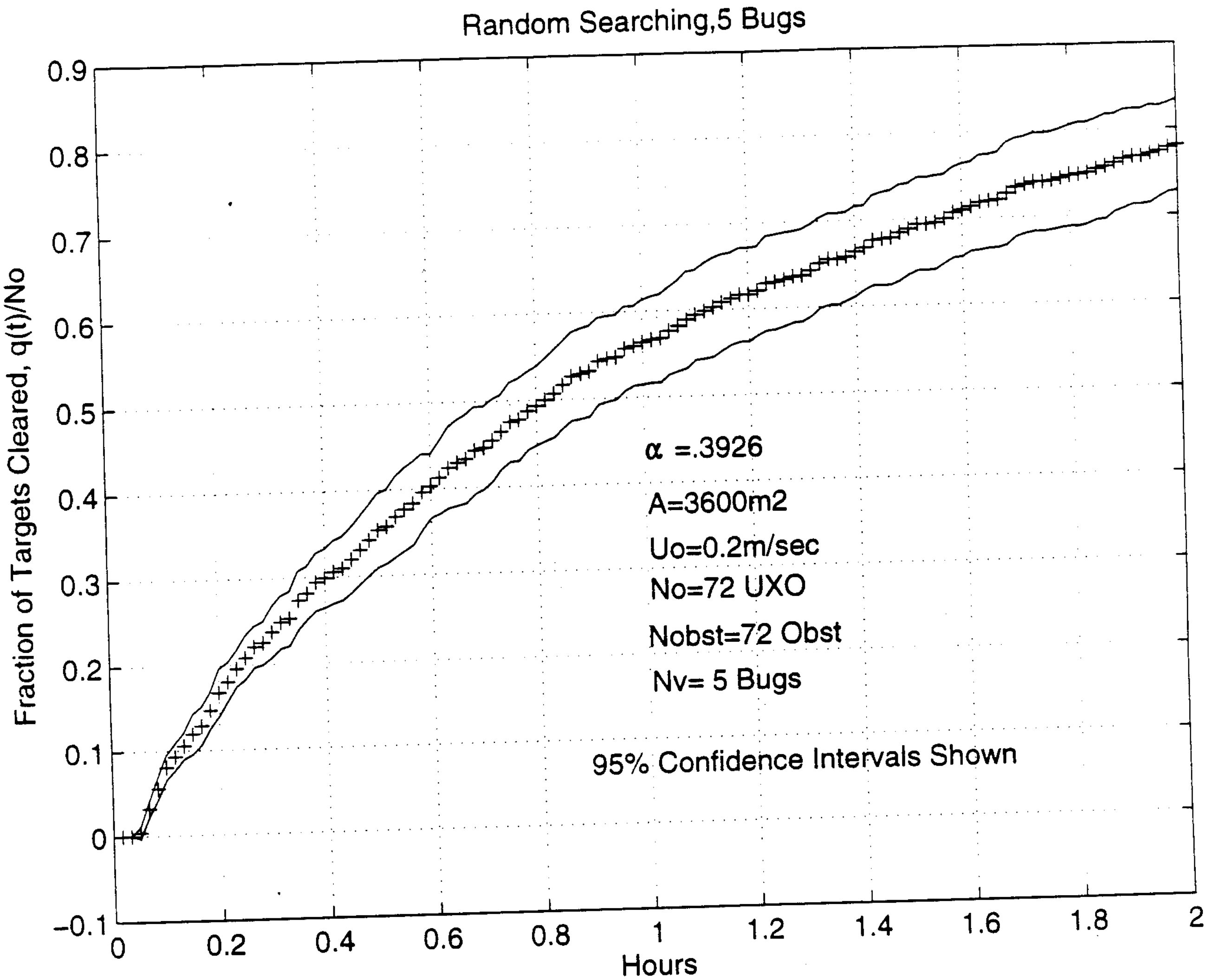


Figure 6.6 Random Searching with Obstacle Avoidance and Disposal

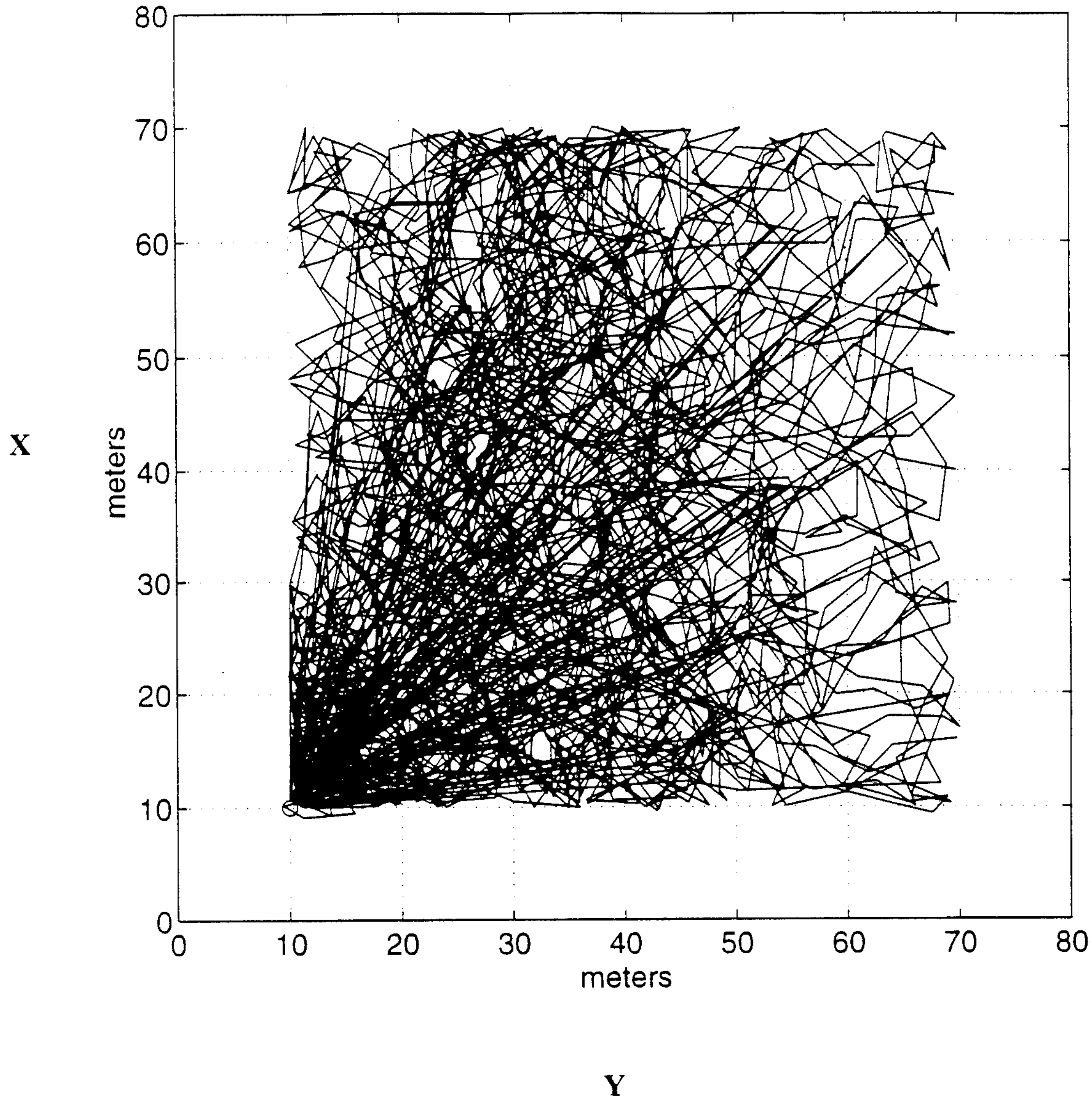
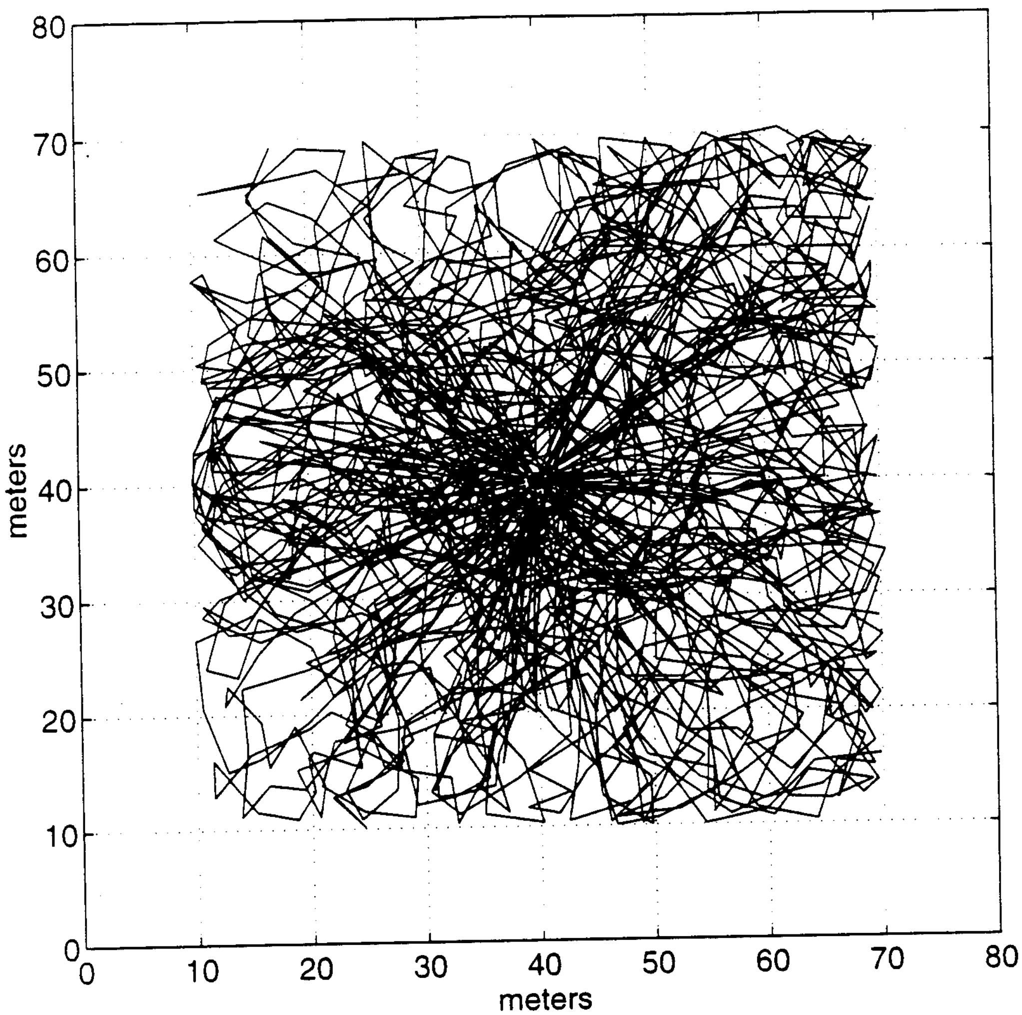


Figure 6.7 BUGS Paths, for One Disposal Point in Corner

X



Y

Figure 6.8 BUGS Paths, for One Disposal Point in Center

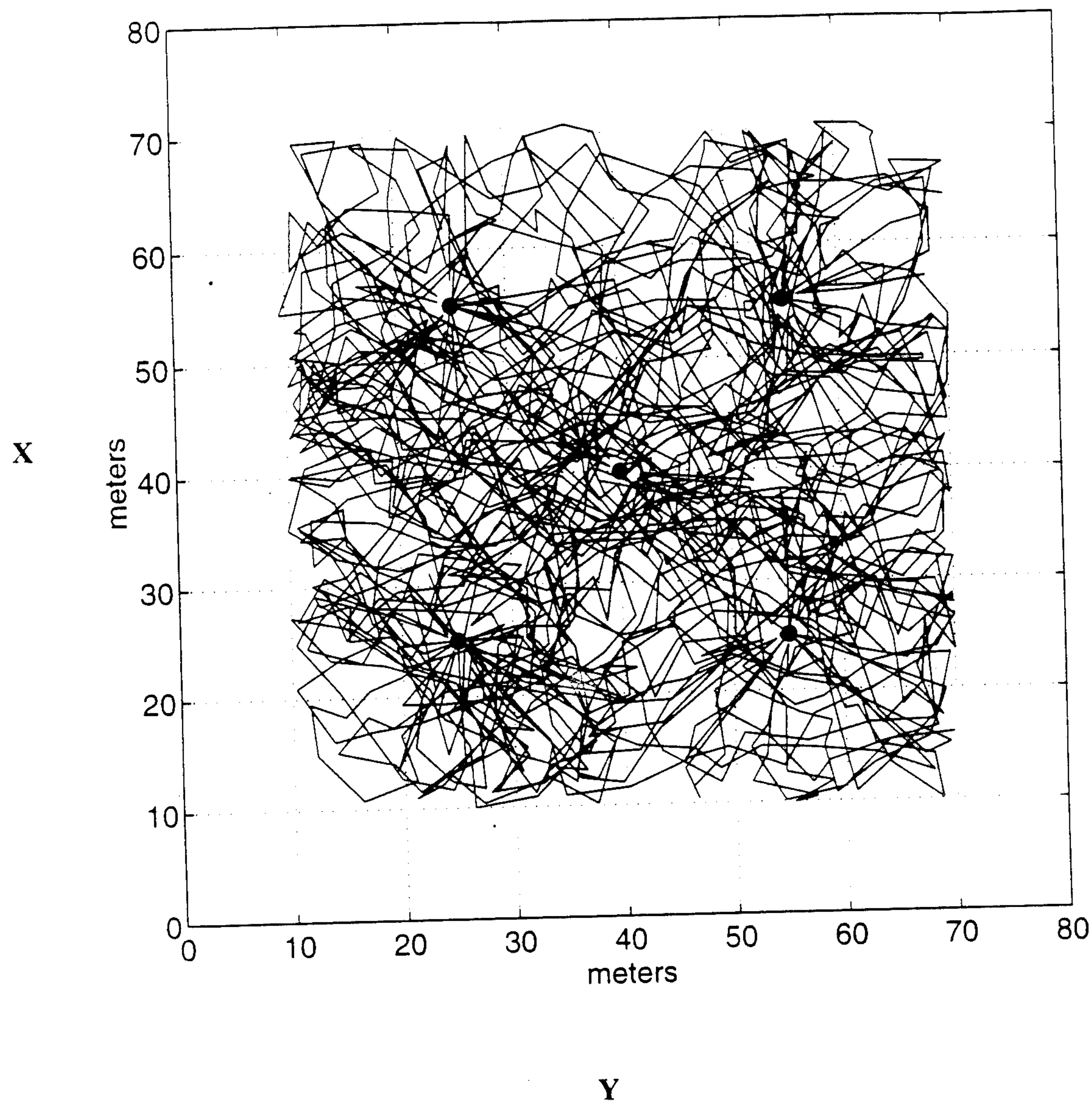


Figure 6.9 BUGS Paths, for Five Disposal Points

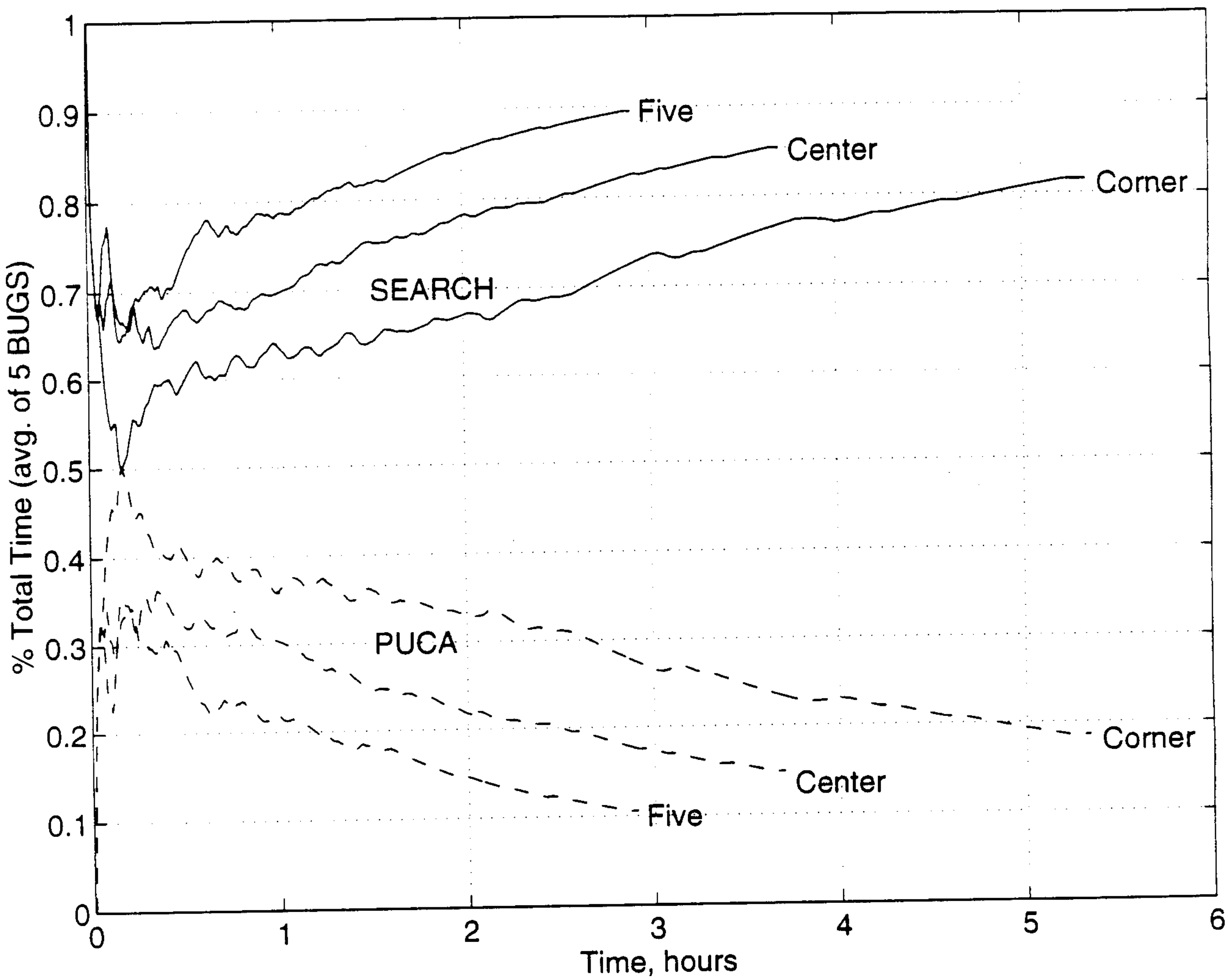


Figure 6.10 Search vs "PUCA" Time Comparison

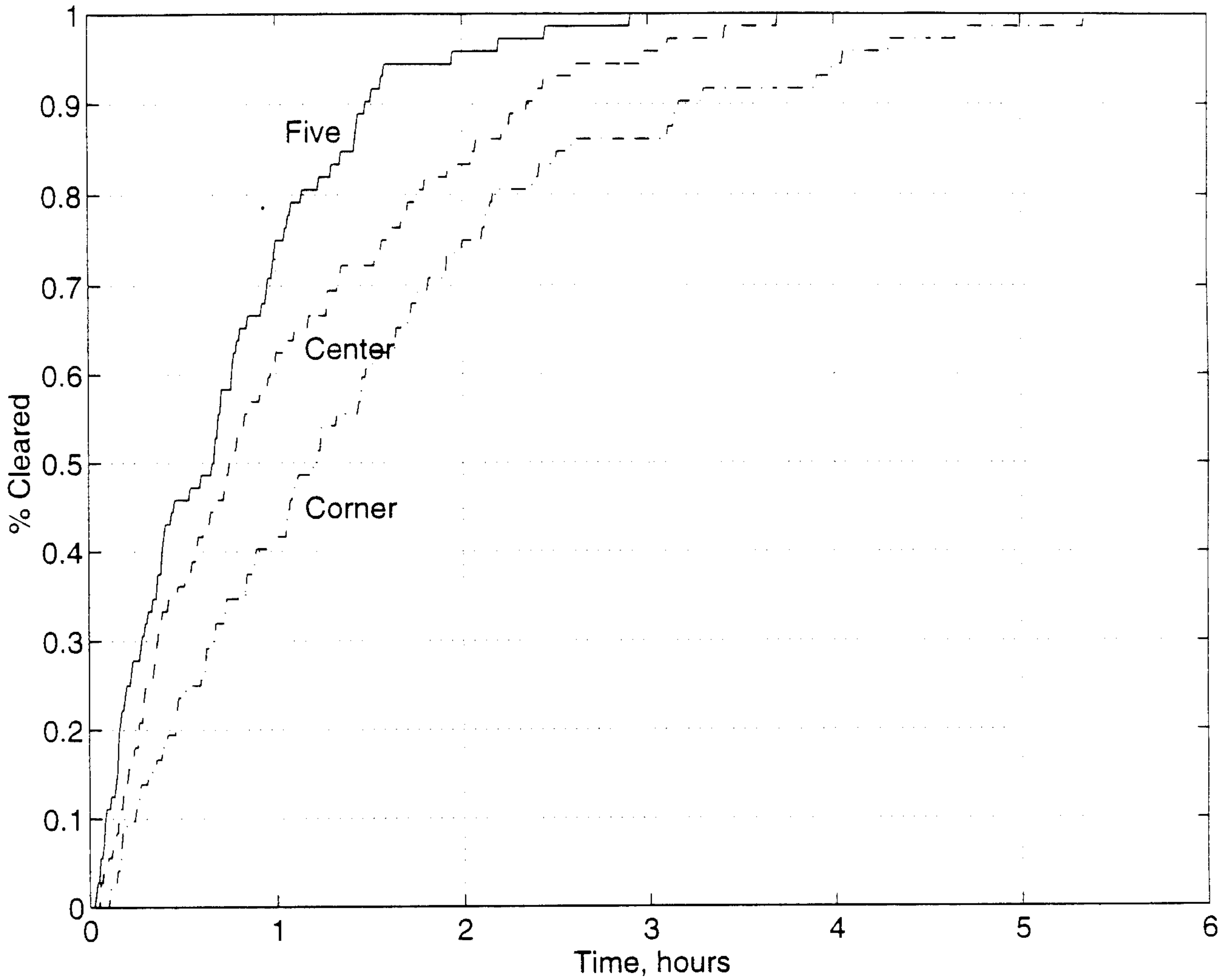


Figure 6.11 Clearance Percentage Over Time for Three Disposal Strategies

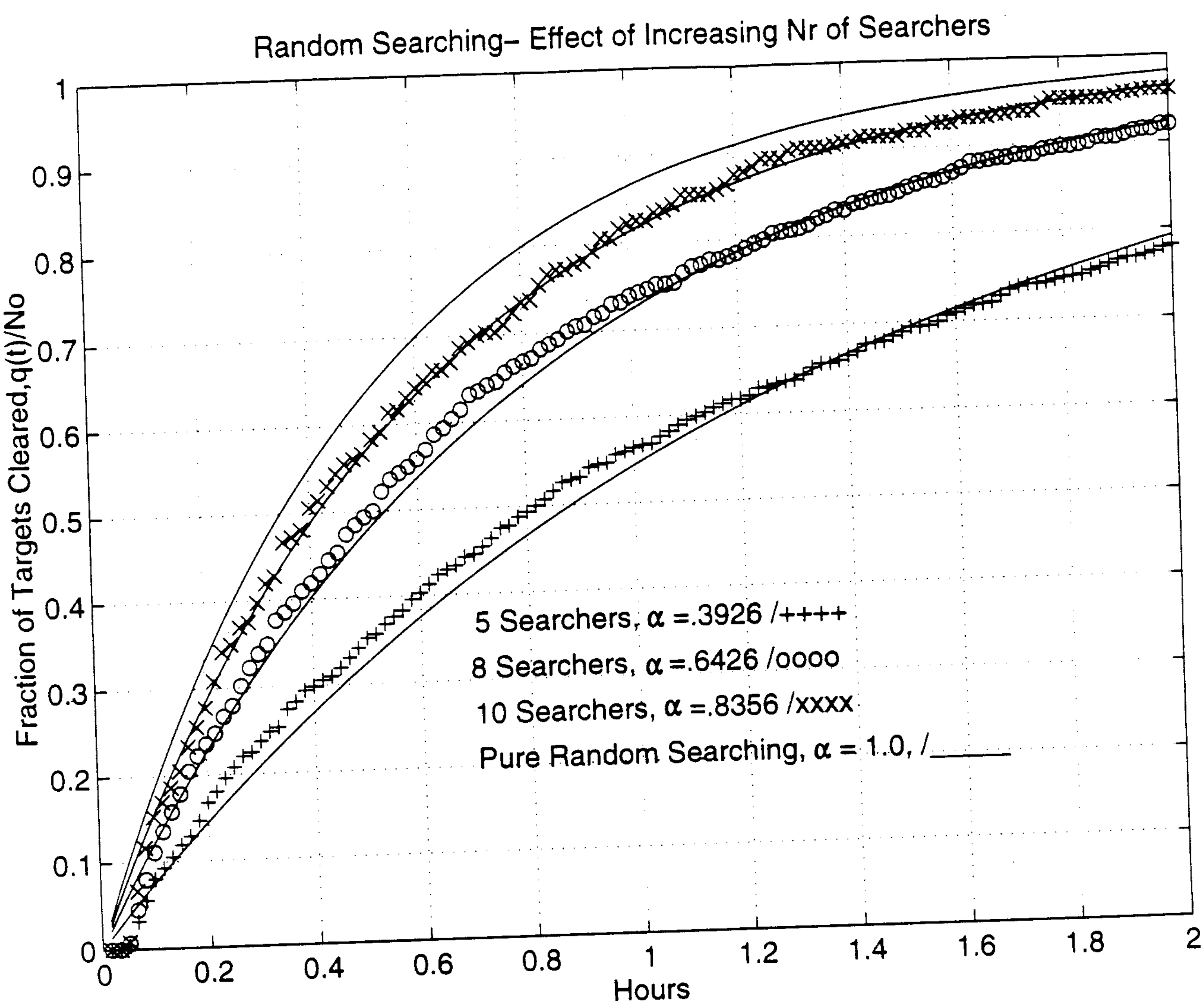


Figure 6.12 Effect of Increased Number of Searchers

VII. CONCLUSIONS AND RECOMMENDATIONS

A. SCENARIO

The overall thrust of this thesis was to examine the relative merits of conducting either an exhaustive or a random search for a fleet of autonomous robots ("BUGS") in a UXO clearance operation. The parameters for the scenario examined are listed in Chapter IV. Essentially, 5 searchers are released into a 60x60 meter area that has been pre-surveyed by either a highly capable autonomous vehicle with very capable sensors and navigation equipment, or by a manned squad. In either case, the UXO's are marked with an acoustic or RF pinger, that the robots can recognize while searching. UXO's are acquired, and then taken to a dropoff point for disposal. Clearance of that UXO is registered upon bringing the UXO to the disposal area.

B. KEY OBSERVATIONS

1. Steering Error vs Clearance

Two key observations have been made in this report. First, it is felt that the basic relationship between percent clearance attained versus steering error is well characterized in Figure 6.1. Search performance from a perfect-navigation searcher in an exhaustive pattern can be expected to return a linear increase in clearance over time. The theoretical "penalty" for a random search, which may arise from poor navigation, follows from the relationship developed in Chapter IV, which goes as

$$1-e^{(-\kappa t)} \qquad (7.1)$$

Imbedded in the random search exponential parameter are search velocity, search width, number of searchers, search area and time. Thus, if we were to conduct a purely

random search, instead of completely covering the field as in an exhaustive search, we get only 63.2 % clearance at a time equivalent to 100% coverage in the exhaustive search case, or,

$$1 - e^{(-1)} \tag{7.2}$$

Figure 6.1 characterizes how clearance depends on the ability to navigate (navigation precision), for the scenario examined. This was a difficult relationship to predict, and one that has no apparent analytical answer. One way to answer the question for a particular scenario is to run a number of simulations and characterize the relationship empirically. Logically, there should be a penalty that results from poor navigation, but the form of the relationship is not intuitively evident.

There is a difference between navigation precision, accuracy, and steering error. The simulation variable steering error was chosen as a convenient way of implementing in a simulation the effects of an increasingly poor positioning/steering control on rough terrain. There is no attempt made here to state or propose a relationship between steering error, precision, and accuracy, beyond the fact that (1) they are certainly related, and (2) it could logically be argued that the introduction of steering error has a negative effect on the ability to navigate precisely.

The curve of Figure 6.1 has a decreasing exponential appearance, and is fitted well with the relationship shown. It shows that as the steering error approaches only approximately +/- 10 degrees, the penalty rapidly approaches that of random steering, as shown by the asymptotic approach to the value of Figure 6.2 at the same time (1/2 hour, 56%).

The question then arises: If we can't get a bug to navigate fairly closely to its desired track without a sophisticated (expensive) navigation and control package, why not simply admit to the random search environment, and equip the bug with rudimentary, (inexpensive) steering? It would be unreasonable for a bug to maintain within a few degrees or so of its

heading on rough terrain, in order to reap the costly benefits of exhaustive search.

2. The Penalty for Obstacle Avoidance and Disposal Transit

The second key point of the thesis is to characterize the penalty that is paid for obstacle avoidance and transit to a disposal point. Figure 6.6 shows that when 5 bugs are deployed with a center disposal point and "random" steering, the resulting clearance performance is markedly below that of the random search curve. This is almost certainly due to the fact that the bugs are frequently off task, while enroute to the disposal point for dropoff. So for that period of time, there is a net loss in searchers in the field. The performance curve fits an increasing exponential fairly well. There is a 40% penalty to be paid for obstacle avoidance and disposal transit.

3. Summary

In summary, then, there are two key observations from this work. The first is that for the scenario examined, the steering error versus clearance curve drops in exponential fashion toward the equivalent random performance. This phenomenon suggests that unless very precise steering can be achieved, one cannot reap the benefits of exhaustive search. Since a substantial portion of the vehicle cost would be absorbed by a precise navigation and control system, it is felt that a better design strategy would be to simply avoid the precise navigation issue, and let the vehicles steer with a rudimentary steering system, to be restrained in the operational area by a simple RF/wire restraint system.

The second observation is that there is a substantial penalty for disposal transit and obstacle avoidance. Since the vehicles are essentially off-task temporarily, there is a reduction in search performance for this scenario to approximately 40% of the exponential value for random search.

C. RECOMMENDATIONS

There are a number of recommendations for further study that are suggested by this thesis. They include issues regarding sensor characterization and performance, bug performance, obstacle density, and dropoff area location. All of these issues could be explored further in order to gain a deeper understanding of the search performance anticipated for these walking machines.

1. The Effects of an Imperfect Sensor.

There are at least two simulation scenarios that could be examined with regard to sensor performance. First, the effects of an imperfect sensor, that is, a sensor operating at 80% effectiveness could be examined. Bugs could detect only 80% of the targets that they encounter. Further, as the sensor systems for autonomous search vehicles evolve, the rules associated with the sensor could be made more representative of the actual sensor performance. This might not be simply applying an 80% probability of detection to an encounter, but might involve a sensor whose performance is sensitive to distance and time, in nonlinear fashion (e.g. for a magnetic sensor).

2. Bug Density Limits

It seems reasonable to examine whether there is there an upper limit in terms of number of bugs, where there might be a degradation caused by continuous avoidance, and possibly "trapping" of the bugs. At some point this might suggest that the field would be so "bug-dense" that there would be a drop in clearance performance.

3. Multiple Dropoff Points

The quantitative effect of adding multiple dropoff points, in strategic geometric positions in the search field could be examined. Although Figures 6.7, 6.8 and 6.9 provide a qualitative observation regarding the attractive effect of various possible disposal point locations, it would seem prudent to make a quantitative comparison between the clearance achieved in each case.

4. Multiple UXO Carry

It is reasonable to expect that each bug might carry 2 or more UXO's, provided that the bug had a "carry-pouch" or some similar carrying tray. Thus, it would be logical to examine whether there is a clearance/time advantage to having multiple-UXO carrying bugs, i.e. the bugs can carry 2 or more UXO's simultaneously to the dropoff point

5. Obstacle Density vs Clearance Performance

The relationship between obstacle density and clearance performance could be explored. The question to be answered might be, " How does one characterize the penalty with respect to clearance time as obstacle density increases? ".

6. Software

Although the speed of each simulation in this work was tenable, if future work is to evaluate more complex disposal and obstacle avoidance algorithms, or increased number of vehicles or targets, it may prove beneficial to convert the code to the ' C ' programming language in order to reduce the run time per simulation.

APPENDIX A. BOUNDARY (PET RESTRAINT) SYSTEMS

A. GENERAL PRINCIPLES OF OPERATION:

On all of the listed RF based systems, a transmitter is used to propagate an AM band RF signal (one system quoted 600 Khz), through a continuous loop of typically 18 gauge wire, that is intended to encircle the area wherein the pet is intended to remain. A typical range where the collar is actuated is 6 - 10 feet. Most system brochures state that this range is adjustable, and there is typically also a two step stimulation feature, whereby the pet is first warned, and then the collar provides the "corrective" stimulus (electric shock). Some systems quote also a "run through" feature, where the system initiates the corrective stimulus at some specific range, regardless of the speed that the pet runs through the fence (i.e. not based on delay). Also, some systems provide for a timeout in the event the pet becomes "trapped" in the fence. 500 feet of wire is typical on smaller systems, but one larger system ("Radio Fence") can surround 100 acres (This would be a square with 636 m sides).

One system, called the "Sonic Fence" System, works by propagating an acoustic beam (directional, conical) on the periphery of the area. 4 posts are used for 300 feet of "fence". The collar receiver picks up the signal, and triggers, much the same as the rf based systems. One advantage this system has is that the posts with the beacons are battery operated and stand alone to create the edge of the area. No wiring is required, as each post has its own transmitter. (Naturally, the posts must be properly oriented to function correctly).

B. SYSTEMS AVAILABLE

1. 'Dog Watch': (Available from RC Steele Co.) System operation is via an RF signal from wire on or in the ground, that triggers the collar.Cost is $445 per kit, includes 500 ft of wire, transmitter and one collar ($ 166 Per extra collar, $40 per extra 500ft wire)

2. 'Home Free' containment system (Available from RC Steele Co. manufacturer is Innotek Pet Products Inc. Operation is via a 600 Khz RF signal from wire on/in the ground, that triggers the collar. Cost is $ 197 per kit, includes 500 ft of wire, transmitter, and one collar

($ 78 per extra collar, $39 per extra 500ft wire)

3. 'Yard Ranger' (Available from RC Steele Co.) Operation is via RF signal from wire on/in the ground that triggers the collar. Cost is $ 298 per kit, includes 500 ft of wire, transmitter, and one collar ($ 129 per extra collar, $40 per extra 500ft wire)

4. 'Sonic Fence' System (Available from RC Steele Co.) Operation is via acoustic beacons affixed to above ground posts. Cost is $330 per kit, includes 4 posts, batteries, and one collar (4 posts provide 300 linear feet of fence).

5. 'Radio Fence' Containment System. Operation is via RF signal from wire on/in the ground, that triggers the collar. Cost is $ 149 per kit, includes 500 ft of wire, transmitter, and one collar ($49 per extra collar, $43 per extra 500ft wire)

APPENDIX B. NAVIGATION SYSTEMS

A. GENERAL

As part of the initial research, a survey of a variety of potential sources for a precise navigation system were contacted. It was originally felt that it should be possible to acquire in quantity a precise navigation system (precision to within one or two meters) that would comprise only a small portion of the target 1K per vehicle postulated. It is recognized that GPS (and DGPS) systems are currently receiving a great deal of interest, however there are several recent promising technologies that may provide a more cost effective solution to the precise navigation suite for walking or tracked vehicles. These include microwave, RF (fm) and cellular systems. Some of these newly developed systems are included in this review.

This review of navigation system options is not meant to be 100% complete, or to reflect the entire industry, or to endorse any particular system , but rather to bring together in one listing both the GPS solution, and several other possible solutions for inexpensive precise navigation of walking or tracked vehicles in a local search area. A brief description of the hardware is provided, the cost of the system as of approximately March 1995, the advantages and disadvantages of the system, and an indication of the accuracy of the system. It is noteworthy that none of the navigation systems could provide a precise navigation (within a few meters) solution for a cost per vehicle in the neighborhood of a few hundred dollars.

B. NAVIGATION SYSTEM OPTIONS

1. No Indigenous Navigation System

a. Hardware: No indigenous navigation system. Let the vehicle travel through the area with some random bearing, and collect it as it exits, or crosses a boundary, or turn it around and allow it to reenter from the other end. This option is the least costly, involving essentially no navigation system. Let the vehicle steer according to then terrain, or its propulsion system. Set up a barrier, i.e. some sort of "fence", that the vehicles can "bounce" against (either physically or by sensing its presence by some sensor) if necessary, in order to remain in the search area.

b. Cost: Cheapest alternative

c. Advantages: Inexpensive, no control system required

d. Disadvantages: Labor intensive, poor positional control over the vehicles. Time consuming to set up barrier, if used. Storage of barrier material, precise placement of boundary material, needed, to avoid actual mined areas. Some degree of risk involved in setup unless mined area boundaries are known fairly precisely.

e. Navigation Accuracy: poor (none)

2. Rudimentary Navigation System (DR-compass-odometer only)

a. Hardware: Rudimentary navigation system (inexpensive compass). Let the vehicle travel through the area on some constant bearing, and collect it as it exits, or turn it around and allow it to reenter from the other end. This option involves the most inexpensive navigation system, perhaps a compass and dr system run by the vehicles odometer. Let the vehicle steer according to some random heading set in at the entry point, and according to the inexpensive compass. Set up a barrier, i.e. some sort of "fence", that the vehicles can "bounce" against (either physically or by sensing its presence by some sensor) if necessary, in order to remain in the search area.

b. Cost: Less than $100, not including "fence"

c. Advantages: Inexpensive, simple system

d. Disadvantages: Labor intensive, poor positional control over the vehicles. Time consuming to set up barrier, if used. Storage of barrier material, precise placement of boundary material, needed, to avoid actual mined areas. Some degree of risk involved in setup unless mined area boundaries are known fairly precisely.

e. Navigation Accuracy: Very poor, nearly random steering

3. GPS indigenous navigation: vehicles calculate position, and navigate accordingly, with periodic GPS updates

a. Hardware: numerous suppliers....Ashtec, Magellan, Rockwell, Micrologic, etc

b. Cost: ($250-500) per unit in quantity, for the least expensive units

c. Advantages: relatively inexpensive (in quantity)

d. Disadvantages: Poor positional accuracy, accuracy insufficient for vehicle to

travel to a known target posit, and then reacquire with current ferrous/magnetic, acoustic or tactile sensors

e. Navigation accuracy: approx 10-20m, position known by vehicle and master control station, if communication relay used

4. Differential GPS: Indigenous navigation (more accurate)

a. Hardware: numerous suppliers (Ashtec, Magellan, Rockwell, Micrologic...)

b. Cost:($750-1100 in qty)

c. Advantages: accuracy to within a few meters or so, Probably best option for position keeping (with cost no object)

d. Disadvantages: Significantly more expensive than GPS; approx 1k per unit, not including communication relay, hardware or master control station hardware

e. Navigation Accuracy: 1-10 meters

5. Non-GPS Radio Frequency Navigation System Option 1:

a. Hardware: 'PINS' , Terrapin Corp, uses 19khz pilot from FM radio stations

b. Cost: $200-300 per board, not including communication software and hardware, cheaper in quantity

c: Advantages: Fairly accurate , inexpensive

d. Disadvantages: Accuracy dependent on many factors, and system, typical 5-25m, dependent on availability of FM radio signals

e. Navigation accuracy: approximately 25 meters

6. Non-GPS Radio Frequency Navigation System Option 2

a. Hardware TIDGET Sensor (NAVSYS) This system utilizes only a portion of the GPS electronics, by receiving the GPS signal on each vehicle, however the navigation solution is calculated at a master station, vice onboard. This allows the vehicle sensor to be less costly, however it does burden the master control station with a large data rate, that would be required were the master control station to be responsible for the simultaneous, real-time position calculations of a fleet of vehicles, in addition to the control signals necessary to affect the vehicles function during the mission.

b. Cost: $300 per sensor, $100 per sensor in large quantity

c. Advantages: Many advantages of GPS, but separation of receiver section from position calculation electronics, allowing onboard sensor to be less expensive

d. Disadvantages: High data rate to/from vehicle

e. Navigation accuracy: 20m GPS, 10m DGPS

7. Non-GPS Radio Frequency Navigation System Option 3

a. Hardware: KSI Inc. Basically a cellular phone direction finding system. System triangulates bearings at 2 or more receiver sites.

b. Cost: 2 receivers at a site approx 60k, cost per vehicle nominal ($30-50), at one cellular transceiver per vehicle.

c. Advantages: Communicaiton link integral with cellular transceiver, Very low cost per vehicle

d. Disadvantages: A startup company looking for funding. Only one prototype system thus far built. Multipath interference is a problem.

e. Navigation Accuracy: 50 meters at 3-5 miles. Company representative says some data showed better than 50 meters, i.e. as good as 10 meters in optimum environment.

8. Non-GPS Radio Frequency Navigation System Option 4

a. Hardware: Sandia National Laboratories; vehicle equipped with low cost transponders, called "tags" (~$100-200 per vehicle) that respond to a 2.4 ghz interrogating signal, from 3 or more transmitter sites. Holds promise as a law enforcement offender monitoring system

b. Cost: $100-200 per vehicle, does not include receiver stations

c. Advantages: Inexpensive per vehicle

d. Disadvantages: Further research needed to ascertain the navigation accuracy at closer ranges, in a small operational area

e. Navigation Accuracy: Nominally 200m at 10-20 miles. Sandia Labs estimates that in a football field sized environment, <10 meters likely.

APPENDIX C. MATLAB SOURCE CODE

This appendix contains the source code for both the random search with obstacle avoidance (and vehicle to vehicle avoidance)simulation, and the steering error versus clearance simulation. Also listed are the subroutines for bouncing back into the search area following dropoff, and the homing routine that establishes the homing basis when necessary.

```
% Cartesian Random Search, with Avoidance, and Disposal
% in One Center DropoffPoint, 60x60m Area, 5 Bugs
%
function [clnc]=bugp24(Nsteps);
%
clear
minep24;
obst24;
op=0;alfa=0;pd=0;clnc=0;
L=.4833333;H=.5166666;
Nt=72;No=72;
Nveh=5;
dt=0.0033333;
%
Nsteps=7200;
x=zeros(Nsteps,Nveh);
y=zeros(Nsteps,Nveh);
y(1,:)=[.0909:.0909:.9090];
Uc=ones(1,Nveh);
count=0;
ctr=zeros(1,Nveh);
ctr1=zeros(1,Nveh);
raddetect=0.0166666;
bugdet=0.0166666;
obstdet=0.008333;
Basis=zeros(1,Nveh);
noise=(pi*rand(1,Nveh)-(ones(1,Nveh)*(pi/2)));
psi =pi*(Basis)+ noise ;
%
 for i=1:Nsteps,
%
% Introduce Steering Error every 5m
%
  if rem(i,25)==0;

       for p=1:Nveh,
              if (rem(Basis(p),.5)==0),
              ctr5=ctr5+1;
              noise=(pi*rand-(pi/2));
              psi(p)=pi*Basis(p)+noise;
              end;
       end;
  end;
```

```
% 2 meter counter
%
  if rem(i,10)==0;
    for q=1:Nveh,
        if (ctr1(q)~=0),
          ctr1(q)==0;
        end;
        if (rem(Basis(q),.5)~=0),
           Basis(q)=homing24(x(i,q),y(i,q));
           psi(q)=pi*Basis(q);
        end;
     end;
  end;
%
% Bug to Bug Avoidance, Distance Matrix Generation and Avoidance Manuever
%
   [xa,xb]=meshgrid(x(i,:),x(i,:));
   [ya,yb]=meshgrid(y(i,:),y(i,:));
   d=sqrt((xa-xb).^2 + (ya-yb).^2);
   D=triu(d);
   [g,h]=find((D<bugdet)&(D~=0));
%
   for n=1:Nveh,
      if (ctr1(n)~=0),
        psi(n)=psi(n);
      end;
      if ((any (g==n)) | (any (h==n)) & (ctr1(n)==0)),
       psi(n)=psi(n)+.5555*pi;
        ctr1(n)=ctr1(n)+1;
      end;
   end;
%
  for veh=1:Nveh,
%
% Step in the "psi" direction by dt*Uc
%
  x(i+1,veh)=x(i,veh)+dt*(Uc(veh)*cos(psi(veh)));
  y(i+1,veh)=y(i,veh)+dt*(Uc(veh)*sin(psi(veh)));
%
% Target Detection
%
  for j=1:Nt,
   st(j,veh)=sqrt((mx(j)-x(i+1,veh))^2+(my(j)-y(i+1,veh))^2);
```

```
% Target Detection if Carrying a Mine, Treating New Mine as Obstacle
% i.e. Bug is Returning(homing), or Basis is Not any of 0,.5,1,1.5
%
    if ((st(j,veh)<raddetect)&(rem(Basis(veh),.5)~=0)),
       psi(veh)=psi(veh)+.5555*pi;
    end;
%
% Target Detection if searching w/o carrying a mine (Basis is 0,.5,1,1.5)
% i.e mine is to be acquired
%
    if ((st(j,veh)<raddetect)&(rem(Basis(veh),.5)==0)),
        ctr(veh)=ctr(veh)+1;
        mx(j)=(-.05);my(j)=(-.05);
        Basis(veh)=homing24(x(i+1,veh),y(i+1,veh));
        psi(veh)=pi*Basis(veh);
    end;
  end;
%
% Obstacle Avoidance
%
   for m=1:No,
    obstdist(m,veh)=sqrt((ox(m)-x(i+1,veh))^2+(oy(m)-y(i+1,veh))^2);
      if (obstdist(m,veh)<obstdet),
         psi(veh)=psi(veh)+.5555*pi;
         x(i+1,veh)=x(i,veh);
         y(i+1,veh)=y(i,veh);
      end;
   end;
%
% Dropoff Area Check and Reversal
%
  if ((x(i+1,veh)>=L)&(x(i+1,veh)<=H)&...
    (y(i+1,veh)>=L)&(y(i+1,veh)<=H)&(rem(Basis(veh),.5)~=0)),
     Basis(veh)=bounce24(x(i+1,veh),y(i+1,veh));
     psi(veh)=pi*Basis(veh);
     x(i+1,veh)=x(i,veh);
     y(i+1,veh)=y(i,veh);
     count=count+1; % Clnc based only on Mines delivered to Dropoff
  end;
%
  if ((x(i+1,veh)>=L)&(x(i+1,veh)<=H)&...
   (y(i+1,veh)>=L)&(y(i+1,veh)<=H)&(rem(Basis(veh),.5)==0)),
```

```
      Basis(veh)=bounce24(x(i+1,veh),y(i+1,veh));
      psi(veh)=pi*Basis(veh);
      x(i+1,veh)=x(i,veh);
      y(i+1,veh)=y(i,veh);
    end;
%
% Turn from Upper boundary
%
    if (x(i+1,veh)>1),
      x(i+1,veh)=x(i,veh);
      y(i+1,veh)=y(i,veh);
      Basis(veh)=1.0;
      psi(veh)=pi*Basis(veh);
    end;
%
% Turn from Lower Boundary
%
    if  (x(i+1,veh)<0),
      x(i+1,veh)=x(i,veh);
      y(i+1,veh)=y(i,veh);
      Basis(veh)=0;
      psi(veh)=pi*Basis(veh);
    end;
%
% Turn from East (right side) Boundary
%
    if (y(i+1,veh)>1),
      x(i+1,veh)=x(i,veh);
      y(i+1,veh)=y(i,veh);
      Basis(veh)=1.5;
      psi(veh)=pi*Basis(veh);
    end;
%
% Turn from West (left side) Boundary
%
      if (y(i+1,veh)<0),
        x(i+1,veh)=x(i,veh);
        y(i+1,veh)=y(i,veh);
        Basis(veh)=.5;
        psi(veh)=pi*Basis(veh);
      end;

  end;
```

```
% Check clearance at some regular interval......
%
   if rem(i,60)==0,
     op=op+1;
     clnc(op)=count/Nt;
   end;
end;
%
% Routine ended, now produce output
%
alfa = Nsteps.*dt.*Nveh.*2.*raddetect;  % Nondimensional par.
pd= 1.0 - exp(-alfa);
%
diary bugout71.dat
alfa
pd
clnc
diary off
%
% Plot output if desired, for inspection
%
%plot(my,mx,'o',oy,ox,'x',y,x,'+'),grid
```

```
% Bugs Testing, Cartesian Exhaustive Search,
% Varying Random Component of Heading
% Plus or Minus 27 Degrees Steering Error
%
function [clnc,count]=bugt77(Nsteps);
%
clear
mines77 ;
alfa=0;pd=0;clnc=0;
Nt=72;
Nveh=5;
veh=1;
dt=0.0033333;
ctrhi=[0 0 0 0 0];
ctrlo=[0 0 0 0 0];
Nsteps=1850;
x=zeros(Nsteps,Nveh);
y=zeros(Nsteps,Nveh);
%
y(1,:)=[.183333 .383333 .583333 .783333 .983333];
%
Uc=ones(1,Nveh);
count=0;
raddetect=0.0166666;
%
noise=(pi./3.3333.*(rand(1,Nveh))-(ones(1,Nveh).*pi./6.6667));
Basis=zeros(1,Nveh);
psi = pi*(Basis)+noise;
%
for i=1:Nsteps,
 for veh=1:Nveh,
%
% Introduce Steering Error every 5m
%
  check=rem(i,25);
    if check==0,
%
        if (Basis(veh)==0)|(Basis(veh)==1.0),
          noise(veh)=(pi./3.3333.*(rand)-(pi./6.6667));
          psi(veh)=pi*(Basis(veh))+noise(veh);
        end;
        if (Basis(veh)==1.5)&(x(i)>=.7),
          noise(veh)= -(pi/6.6667).*rand;
```

```
      psi(veh)=pi*(Basis(veh))+noise(veh);
    end;
%
    if (Basis(veh)==1.5)&(x(i)<=.35),
      noise(veh)=(pi/6.6667).*rand;
      psi(veh)=pi*(Basis(veh))+noise(veh);
    end;
  end;
%
% Target Detection
%
  for j=1:Nt,
   st(j,veh)=sqrt((mx(j)-x(i,veh))^2+(my(j)-y(i,veh))^2);
      if (st(j,veh)<raddetect),
         count=count+1;
         mx(j)=-.05;my(j)=-.05;
      end;
  end;
%
% Step in the "psi" direction by dt*Uc
%
 x(i+1,veh)=x(i,veh)+dt*(Uc(veh)*cos(psi(veh)));
 y(i+1,veh)=y(i,veh)+dt*(Uc(veh)*sin(psi(veh)));
%
% Turn west at upper boundary
%
   if (x(i+1,veh)>1),
     x(i+1,veh)=x(i,veh);
     y(i+1,veh)=y(i,veh);
     Basis(veh) = 1.5;
     psi(veh)=pi.*Basis(veh)-((pi/6.6667)*rand);
     ktr1(veh)=ktr1(veh)+1;
   end;
%
% 2m counter for Lateral Displacement
%
   if (Basis(veh)==1.5)&(x(i+1)>=.7),
     ctrhi(veh)=ctrhi(veh)+1;
     psi(veh)=pi.*Basis(veh);
   end;
%
% If 2m elapsed, turn south
%
```

```
    if (ctrhi(veh)>=10),
      Basis(veh)=1;
      psi(veh)=pi.*Basis(veh);
      ctrhi(veh)=0;
    end;
%
% Turn west at lower boundary
%
    if (x(i+1,veh)<0)&(Basis(veh)==1.0),
      x(i+1,veh)=x(i,veh);
      y(i+1,veh)=y(i,veh);
      Basis(veh) = 1.5;
      psi(veh)=pi.*Basis(veh)+((pi/6.6667)*rand);
    end;
%
% 2m counter for south border
%
   if (Basis(veh)==1.5)&(x(i+1)<=.35),
     ctrlo(veh)=ctrlo(veh)+1;
   end;
%
    if (ctrlo(veh)>=10),
      Basis(veh)=0;
      psi(veh)=pi.*Basis(veh);
      ctrlo(veh)=0;
    end;
%
% If east boundary encountered, reset y position
    if (y(i+1,veh)>1.0),
      Basis(veh) = 0.0;
      y(i+1,veh)=y(i,veh);
    end;
%
% If west boundary encountered, reset y position
%
    if (y(i+1,veh)<0.0),
      Basis(veh) = 1.0;
      y(i+1,veh)=y(i,veh);
    end;
%
   end;
end;
%
```

```
% Output
diary bugout167.dat
clnc=count./Nt;
clnc
diary off
%
% Plot Output as desired
%plot(y,x,'+',my,mx,'o'),grid
%title('Clearance vs Steering Error, (+/-)27  Deg')
%xlabel('Steering Error')
%ylabel('% Clnc')
```

```
% Rules for Bouncing Back Into Search Area
% Following Entry into Dropoff Zone
function Basis = bounce24(x,y)
%
L=.4833333; H=.5166666;
if (x>y)&(y>.5)&(x<H)&(x>.5), % Sector 1
  Basis=0;
end;
%
if (x>y)&(y<.5)&(x<H)&(x>.5), % Sector 2
  Basis=0;
end;
%
if (x>y)&(y<.5)&(x>.5)&(x<H), % Sector 3
  Basis=1.5;
end;
%
if (x>y)&(y>L)&(x<.5)&(x>L), % Sector 4
  Basis=1.5;
end;
%
if (x<y)&(y<.5)&(x>L)&(x<.5), % Sector 5
  Basis=1;
end;
%
if (x<y)&(y>.5)&(x>L)&(x<.5), % Sector 6
  Basis=1;
end;
%
if (x<y)&(y<H)&(x<.5)&(y>.5), % Sector 7
  Basis=.5;
end;
%
if (x<y)&(y<H)&(x>.5)&(y>.5), % Sector 8
  Basis=.5;
end;
%
% Homing Basis Calculation
function Basis = homing24(x,y)
%
if (y>.5)&(x<.5),
   z = 1.5*pi + (atan((.5-x)/(y-.5)));
   Basis=z/pi;
```

```
end;


if (y>.5)&(x>.5),
   z = pi + (atan((y-.5)/(x-.5)));
   Basis=z/pi;
end;
if (y<.5)&(x>.5),
   z = pi/2 + (atan((x-.5)/(.5-y)));
   Basis=z/pi;
end;
if (y<.5)&(x<.5),
  z = (atan((.5-y)/(.5-x)));
  Basis=z/pi;
end;
%
%
% Sample Minefield or Obstacle Generation Routine
%
Nt=72;
%
rand('uniform');
mx=rand(1,Nt);
my=rand(1,Nt);
%
%plot(my,mx,'O')
```

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